Lunar Coordinate Systems, Frames and Geodetic Products

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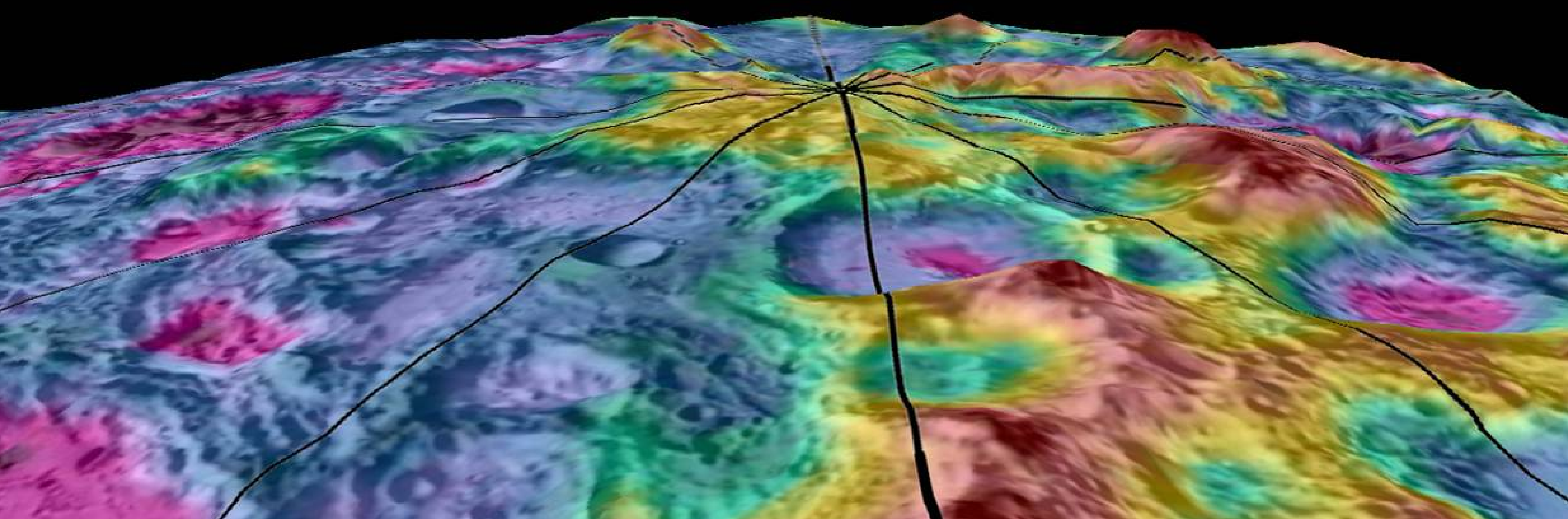


Outline

I. Systems and Frames
- Coordinate Systems and Frames
- Conventions, historical and current
- Dataset Registration

II. Past and Present Frames/Products
- Horizontal Reference Frames and Products
- Vertical Reference Frames and Products

III. Future Control and Products
- Pre (end of) LRO Frames/Products
- Post LRO Frames/Products
- Recommendations & Discussion

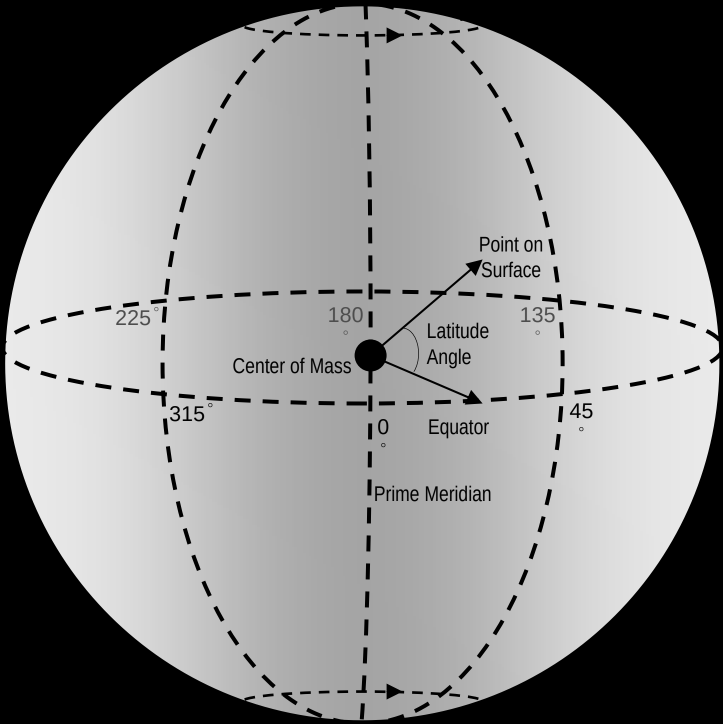
I. Systems and Frames

Some Definitions (not meant to be complete)

- *Reference systems* vs. *frames*
  - System is overall concept, physical environment, theory, conventions forming an idealized model
  - Frame is specific realization of a system, e.g. a solution which defines from observational data a list of point coordinates, usually with associated uncertainties
  - Examples: Sky: ICRS and ICRF; Earth: ITRS and ITRF 2005
  - Useful concept, even though *system* and *frame* often used interchangeably
- Frame examples: photogrammetric *control network;* altimeter solution ground locations
- Systems and frame can be mostly for establishing *horizontal* or *vertical* positions or both
- Frames also sometimes called *datums*
- “height” can be measured in terms of
  - radii, e.g. from center of mass of body
  - distance above a *reference surface* (sphere or ellipsoid)
  - *geopotential height* (*elevation*) above a *reference geopotential surface*, i.e. the *geoid*
- For Moon, height usually measured as radius or height above sphere. Other height systems used on occasion in the past, may be used again in future.

Lunar Coordinate Reference Systems - I

- Two common lunar reference systems:
  - mean Earth/polar axis (ME)
  - principle axis (PA), or axis of figure
  - spherical coordinates
- ME:
  - Mean direction of earth defines 0° longitude, mean rotation pole defines latitude
  - In use in some form since 1775 (Mayer) at least, for almost all cartographic products
  - Adopted by the IAU/IAG
- PA:
  - 3 maximum moments of inertia define axes
  - Important for dynamical (LLR) and gravity field studies (C_{21}, S_{21} and S_{22} are all zero)



Lunar Coordinate Reference Systems - II

- ME to PA difference:
  - 860 m total (560 m in longitude)
  - Due to asymmetry in lunar gravity field, otherwise would be the same
  - “small” but obviously significant
- System orientation:
  - Orientation model for ME system given by IAU/IAG (1994) with closed formulae
  - Orientation model for PA system given via JPL LE 403 ephemeris (from ~1996)
  - ME to PA difference also available as part of LLR solutions (no global rotations of retroreflectors allowed in ME coordinates)
  - ME to ME (IAU/IAG to JPL) is ~105 m, but variable (see Konopliv, et al., 2001, figure 3 at right)
  - IAU/IAG 2006 will use JPL LE 403 and ME/PA difference to define ME system
  - New JPL LE is also expected soon

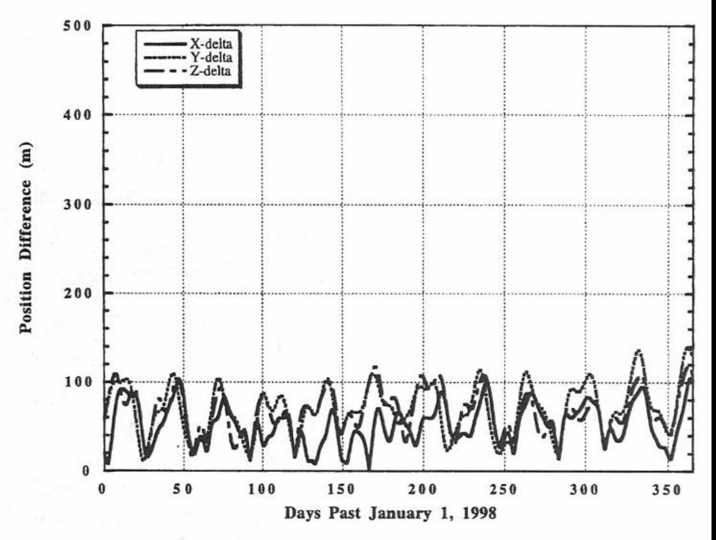
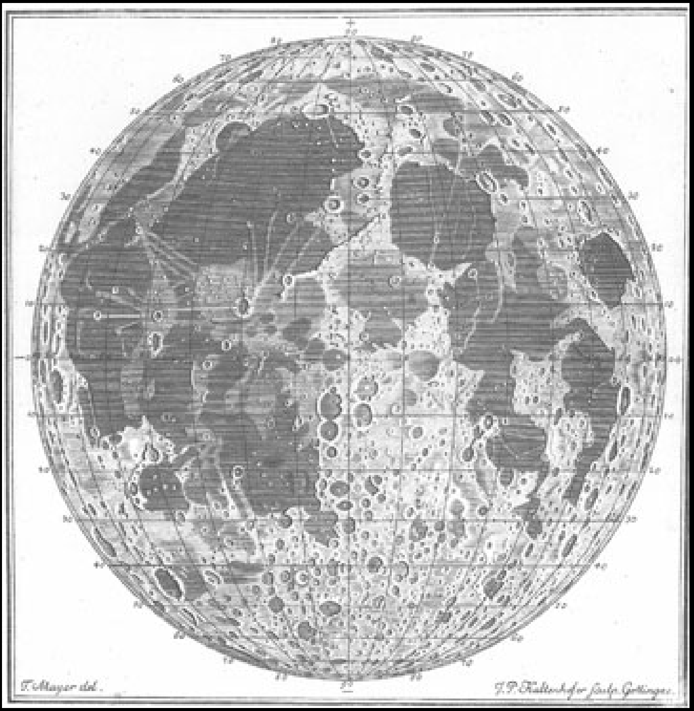


FIG. 3. Differences of the lunar axes on the lunar surface from the DE403 integrated lunar librations and the 1994 IAU mean pole.

Adopted Coordinate System Conventions: Historical

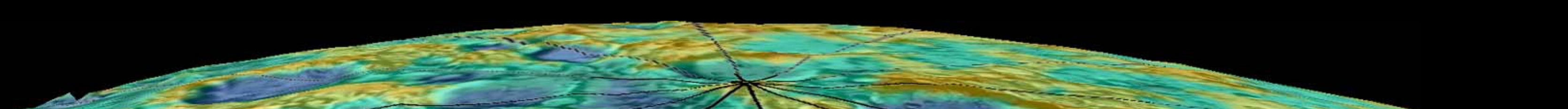
- Spherical coordinates, but (ξ, η) used for a time (1900's)
- Craters *Manilius*, then *Mösting A* used for a time as a fundamental point (1800's on)
- East/west either using sky direction or right-handed system; right-handed system adopted by IAU in 1961
  - Note Mare Orientale is now on the *west* side of the Moon!
- Latitudes -90° to +90°
- Longitudes
  - -180° (west 180°) to +180° (east 180°) *or*
  - 0° to 360° east



Mayer (1775)

Adopted Coordinate System Conventions: IAU/IAG WG

- IAU/IAG WG on Cartographic Coordinates and Rotational Elements
  - ME system, longitudes east and west 180° *or* 0° to 360° east,
  - Prior to 2006, closed formulae for orientation. Now (draft) based on JPL LE 403 & rotations
  - Spherical reference surface: 1980-1985, 1738 km “used since 1960”; 1988-2006, r=1737.4 km, based on Apollo altimeter dataset



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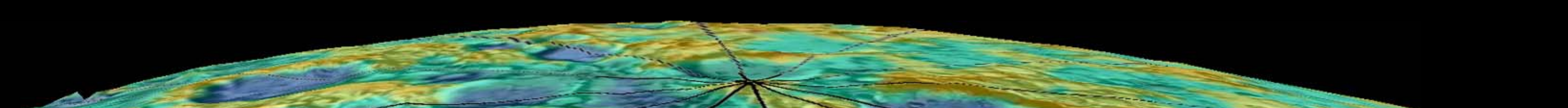
Adopted Coordinate System Conventions: Clementine

- Clementine
  - ME system for products
  - LIDAR archive
    - r=1738 km, 1/f=3234.93 for data and gridded topography
    - r=1738 km for s. h. topo model (GLTM-2B)
    - Compared to r=1737.4 km recommended by IAU/IAG WG

- Also, compare to mean radii (km):
  - Clementine lidar: 1736.87, σ=2.3, range (-10.7, 7.4)
  - Apollo lidar: 1737.38, σ=2.4, range (-7.5, 5.6)
  - ULCN 2005: 1736.93, σ=2.1, range (-10.6, 12.3)

Adopted Coordinate System Conventions: LRO

- LRO
  - Adopted by LRO Data Working Group
    - "A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter," LRO Project White Paper, 2006 August 23
  - ME system for products
  - PA system can be used internally
  - longitudes 0° to 360° east
  - ME orientation (specific frame) defined by JPL LE 403 & rotations (and improved LE when available)
  - Reference surface not yet adopted



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Adopted Coordinate System Conventions: DISCUSSION

- Can consensus be achieved on one system?
- Start with LRO LDWG model?
- Other NASA components?
  - LPRP likely to follow (meeting last month at NASA Ames)
  - Constellation Program draft was using PA system only, likely will switch to using ME system
- What will foreign missions use?
  - Can we reach some consensus here?
  - Note that Chandrayaan-1 may be using reference sphere of 1738 km (J. Boardman, pers. comm.)
- Additional discussion likely needed here and later on reference surface, gravity field, geoid, etc.
- IAU/IAG Working Group could help
- NASA Working Group – with international input?
  - MGCWG provides such coordination for Mars. Is a LGCWG needed?

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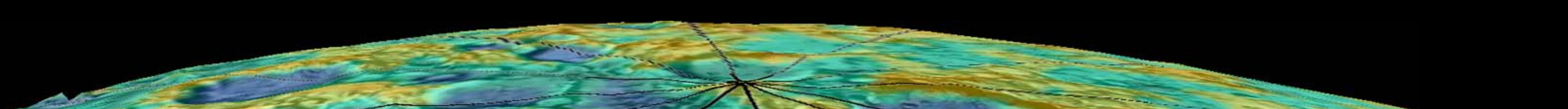


Dataset Registration

- *Either* “dead-reckon” into correct system
  - Use navigation or measured spacecraft position, pointing
  - *Uncontrolled* mosaics
- *Or* tie together, e.g. “control” with Photogrammetry or radargrammetry
  - Least squares adjustment of position and pointing, recovery of uncertainty estimates
  - *Controlled* mosaics (e.g. MDIMs, numerous other USGS products)
  - Sometimes provides densest and most accurate frame as well
- *Or* “semi-controlled” as concession
  - Image matching at least (e.g. THEMIS IR mosaic)
  - Possibly quick
  - Difficult (not demonstrated) at sub-pixel level, uncertainty unknown?
- For now, as data is added to existing solutions, frame accuracy and density is improved
- While frame is evolving, products (ideally) need to be regenerated after each improvement
- Once frame stabilizes, task becomes integration of new data into it (has happened with Mars MOLA, will happen for Moon with LOLA tied to LLR)

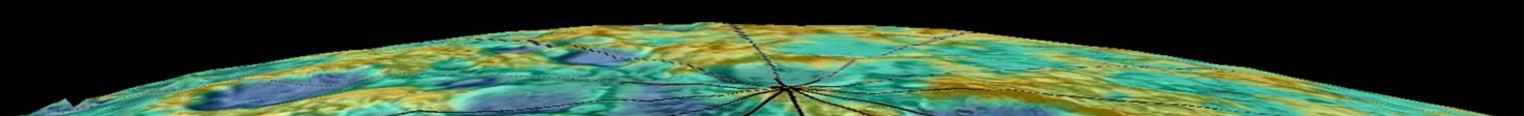
The Need for Control of Image Datasets

- Only way to connect/register/compare data at known levels of precision and accuracy
- Data cannot be compared with confidence and synergistic value of datasets lost otherwise
- Users always want best precision and accuracy possible and want to know what it is
  - important for mineralogic, geologic, and scientific investigations
  - *critical* for landing and landed operations
  - lander maneuvering costs and danger (including loss of mission) rise significantly with uncertainty. C.f. Apollo 11, 12, 15 landing problems
- Best way to remove seams for qualitative work
- Necessary for proper orthometric projection of data (registration of images to topography)
- Necessary for registration of multispectral data
- Note that usually considered “expensive”, but not so relative to the cost of data collection, or worse, the inability to use the data or the loss of a mission

II. Lunar Coordinate Reference Frames

Past through the Present:

- ✦ Early (space-age) networks
- ✦ LLR/ALSEP (1969-present)
- ✦ Meyer, D. L. (1980)
- ✦ ULCN: The Near Side (1987)
- ✦ ULCN (1994)
- ✦ CLCN (1996)
- ✦ ULCN 2005



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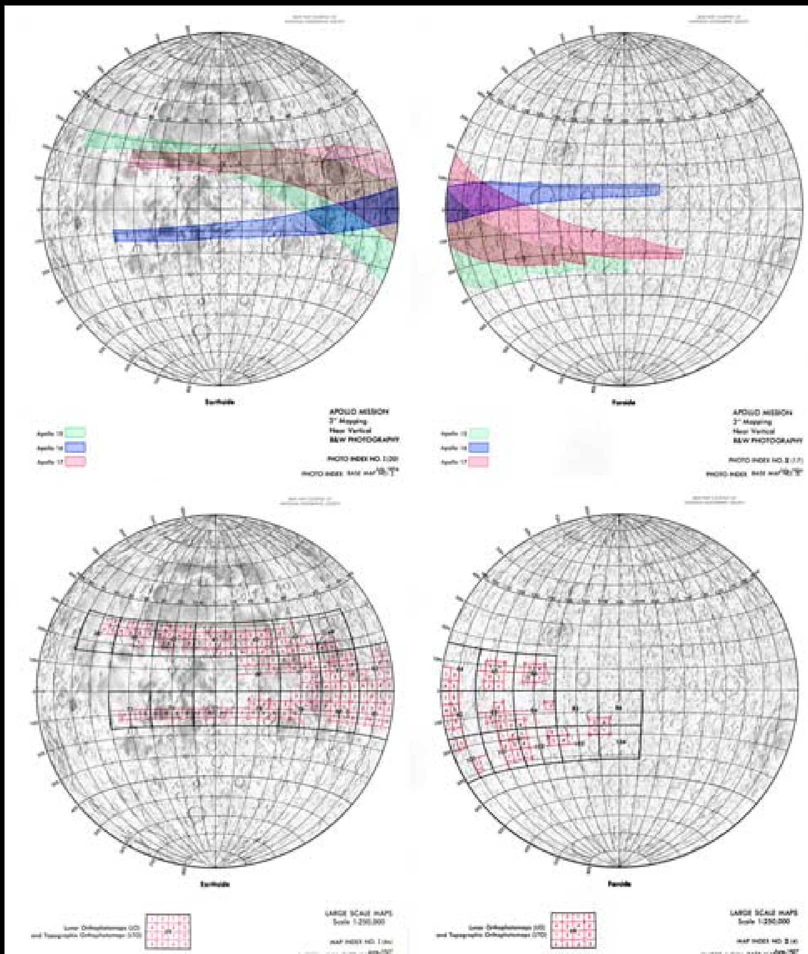
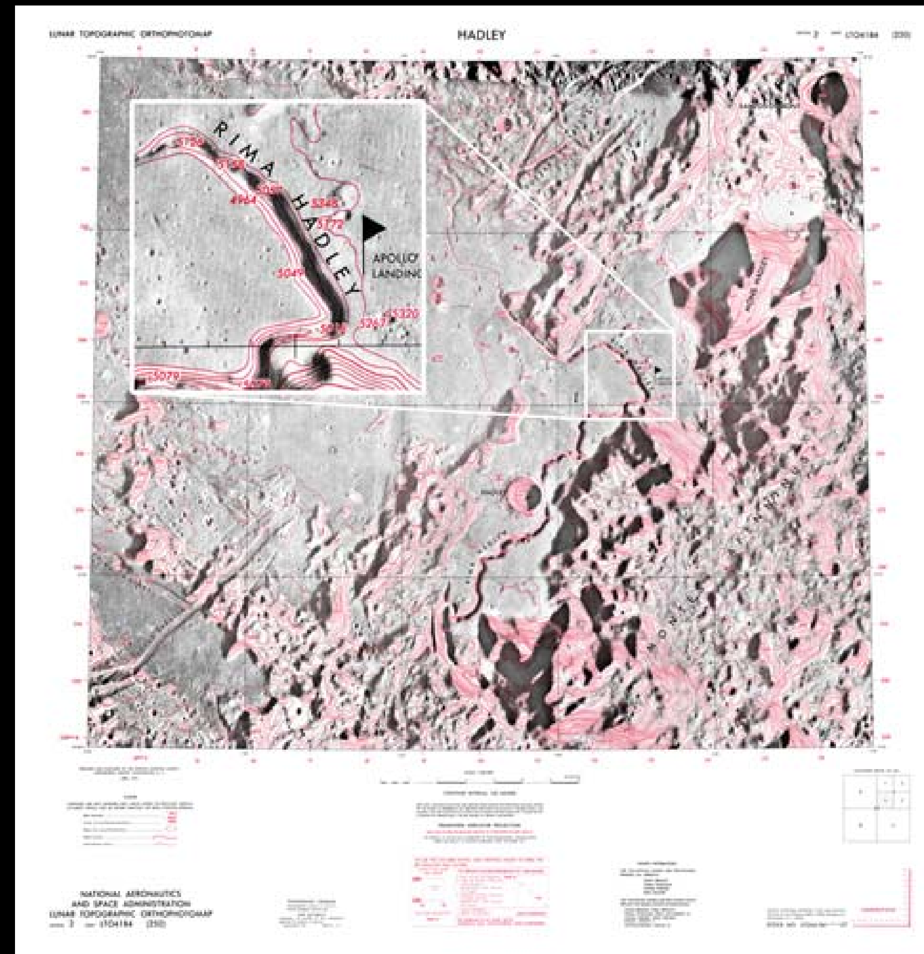
Early Coordinate Frames

- Historical, space age through the 1970's
- Lunar Dossier (1977 rev.) lists, for mapping support:
  - 10 global systems
  - 4 regional systems (including LLR/ALSEP)
  - 39 (LO) and 2 (Apollo) local systems
- Now mostly of historical interest
- However:
  - Topographic products still useful regionally, until new altimeter datasets become available
  - Topographic products still useful locally, even post LRO (few m contours), if reregistered
  - Apollo network(s) should be restored or redone, possibly to strengthen existing ULCN in near term, mostly to tie still valuable Apollo images to post LRO network(s)
  - DMA Catalog of Lunar Positions (CLP) (1975) points used in ULCN

Examples: Apollo zone coverage, LTO charts



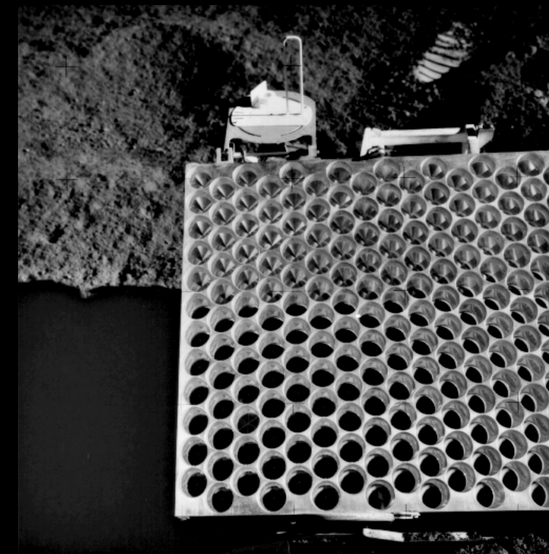


http://www.lpi.usra.edu/resources/

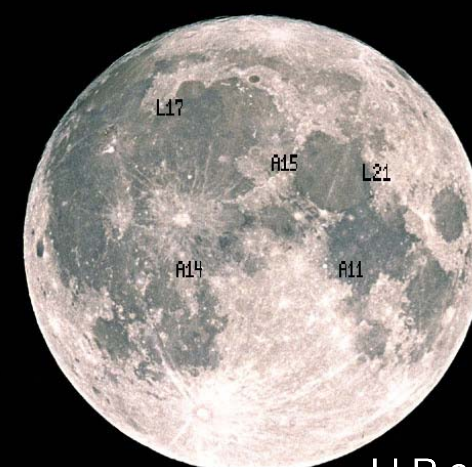
LLR/ALSEP

- Positions of Apollo 11, 14, 15, and Lunokhod 2 (Luna 21) retroreflectors measured, 1969-present, via LLR
- Sub cm accuracy
- Positions of Apollo 12, 14, 15, 16, 17 sites (EASEP/ALSEP packages) defined by Mark II VLBI in 1976 (King, et al., 1976)
- Meter level accuracy
- Most accurate frame(s) by far, but few points
- Used to define orientation (librations) of axis of figure frame, and in turn mean Earth/polar axis frame
- Many other users: Lunar orbit, tides, core characterization, relativity tests, and Earth orientation, precession, nutation determination
- Nearby features located by Davies and Colvin (2000), with decimeter accuracy

→ Should be used to orient future frames such as LOLA derived, e.g. via images or Apollo site DTM matching

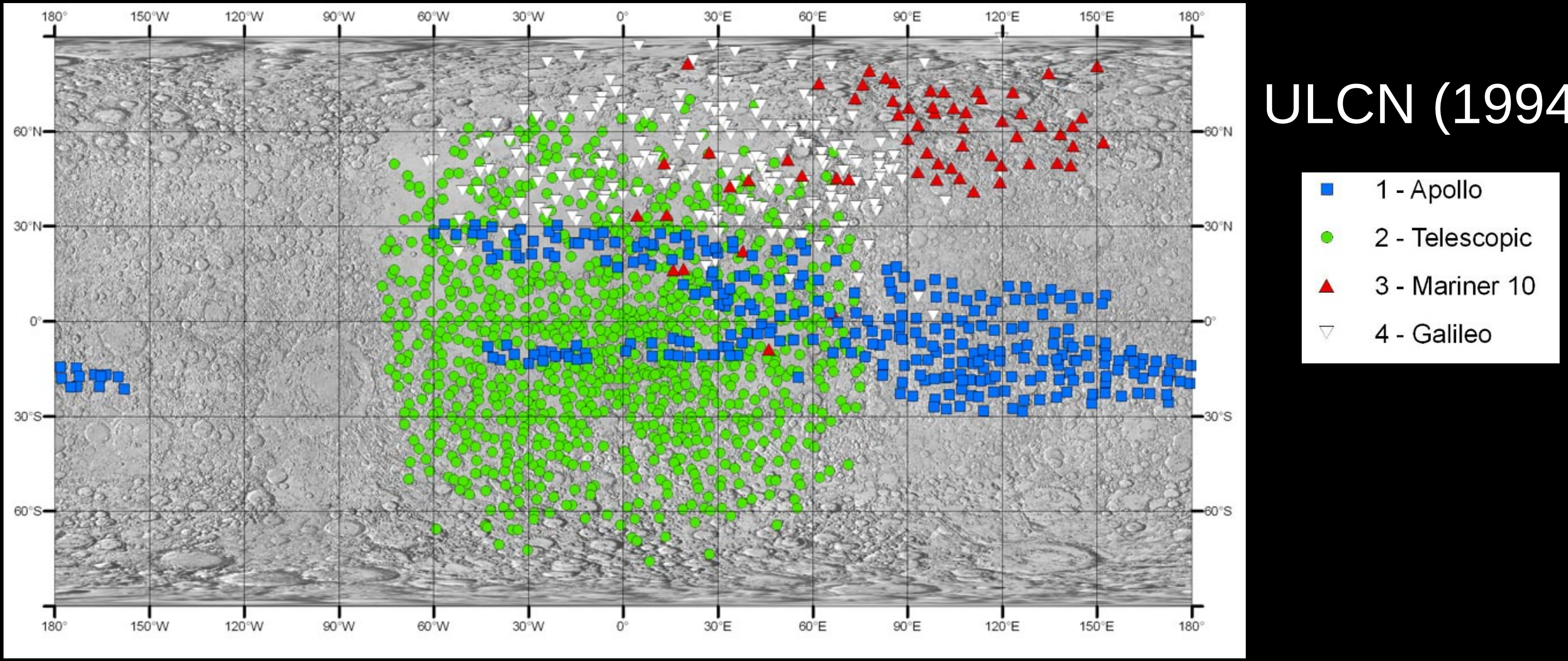


Apollo 15 retroreflector array



LLR array sites

Unified Frames



ULCN (1994)

Work by Donald Meyer, Sandra Nelson (DMA) and Mert Davies and Tim Colvin (Rand) to combine existing (1980's) data

- Meyer (1980): From telescopic images (10 USNO 61-inc plates), 1156 points
- ULCN (1987): Near side, added LLR/ALSEP, Apollo data, to orient and place at COM. 10 Mariner 10 points.
- ULCN (1994): Extending to poles and far side. Added Apollo, Mariner 10, and Galileo control. 1478 points total, 1286 near side, 192 far side
- Estimated accuracies (1994): Apollo (100 m near side, 500 m far side), Galileo (1-1.5 km), Mariner 10 (1.5-2 km), telescopic (2-3 km)

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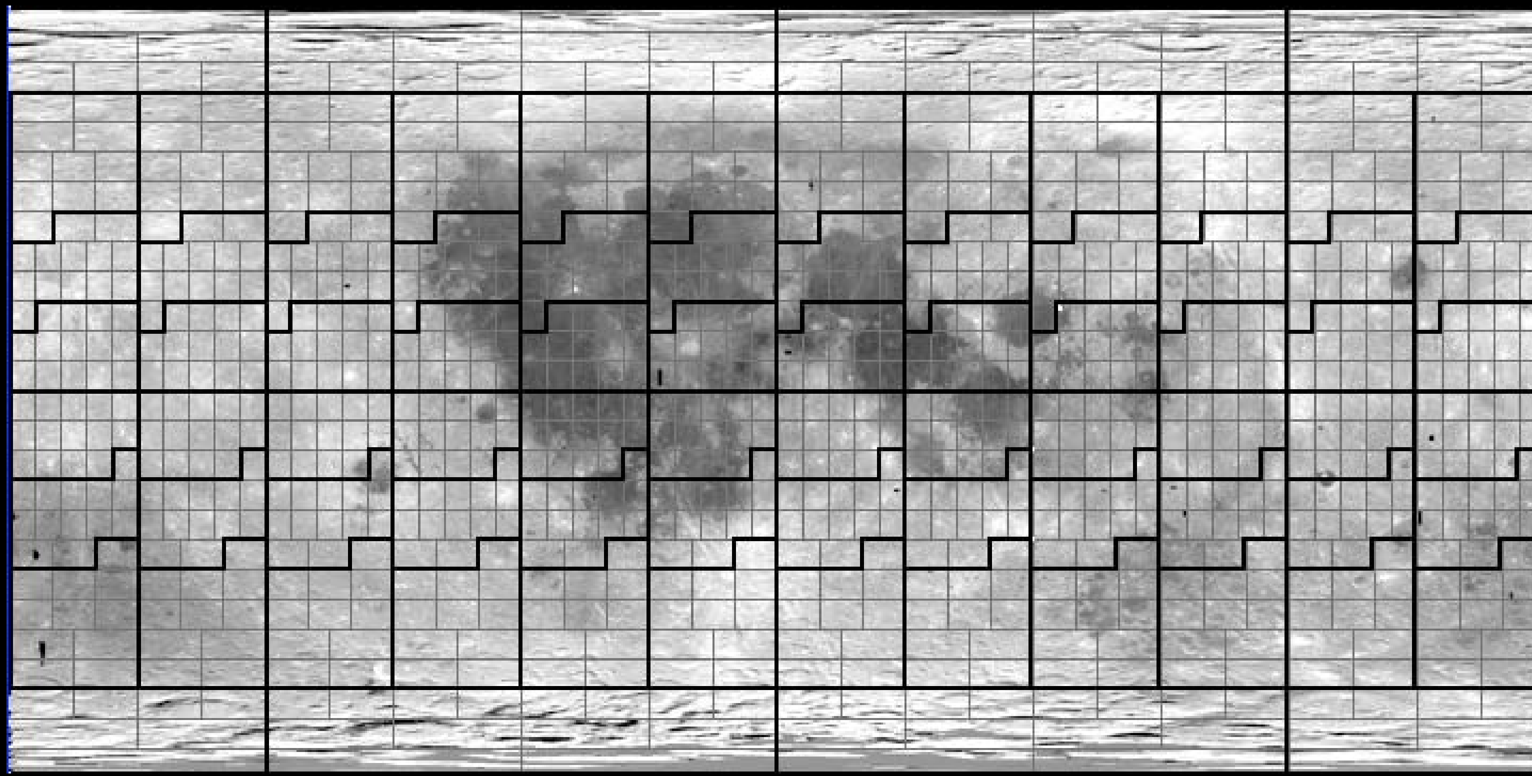
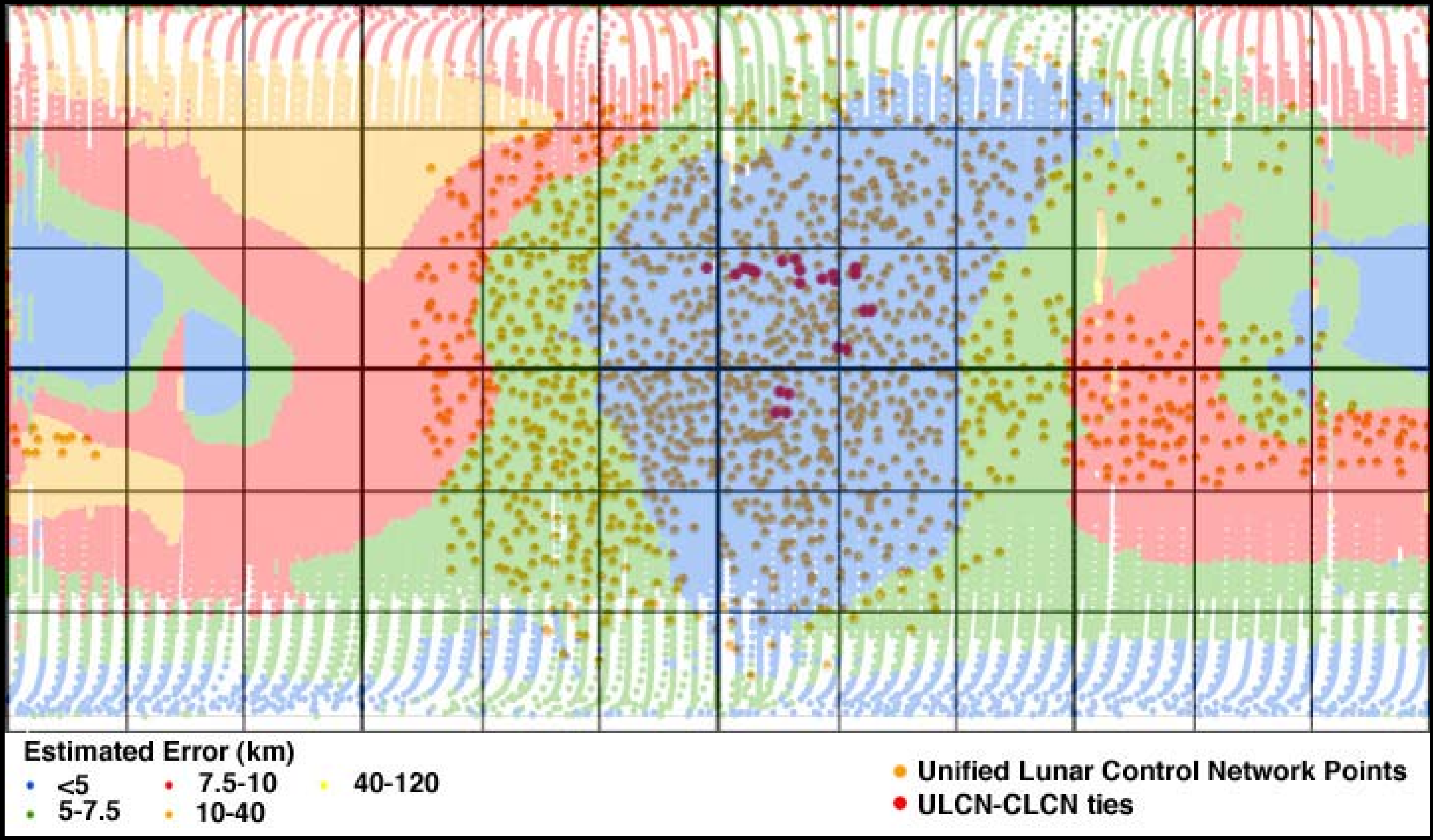
Clementine Lunar Control Network (CLCN) and Mosaics



- CLCN created to control ~43, 871 (mostly 750 nm) images. 543, 246 measures of 271,634 points. Other images co-registered
- Over 2,000,000 images from UV-Visible and Near IR cameras. Global mosaics (basemap, UVVIS, NIR; 15, 78, TBD CDs) generated at 100 m GSD: 110,000x55,000x11 bands
- Commonly used by default for measuring lunar coordinates

CLCN Problems



CLCN shows shifts averaging ~7 km and up to 20 km and more from a priori info. Why? 1) Angles not constrained; 2) Few ties to earlier unified net ULCN (red dots); 3) *CLCN points assumed to lie on a sphere*

→ *Clementine mosaics show same distortion*

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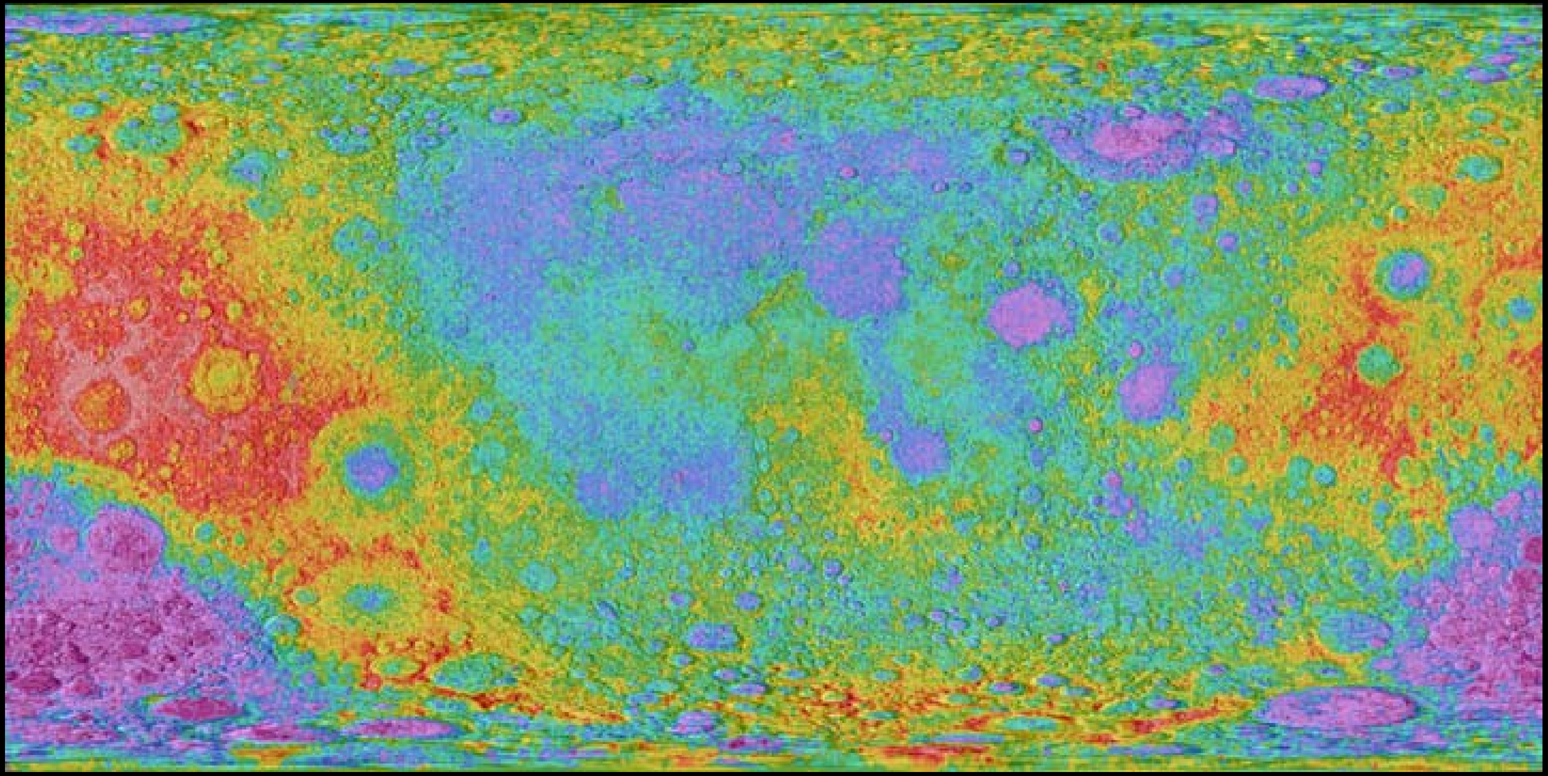
Unified Lunar Control Net 2005



ULCN 2005: Recalculate CLCN with 1) All possible ULCN points included; 2) Appropriate weights for a priori pointing; 3) *Solve for radii of points*

⇒ *Greatly improved horizontal positions (~1 km accuracy?)*

⇒ 272,931 points vs. ~70,000 for Clem LIDAR make this the *densest available global DTM for the Moon.* Shown above with USGS airbrush topography

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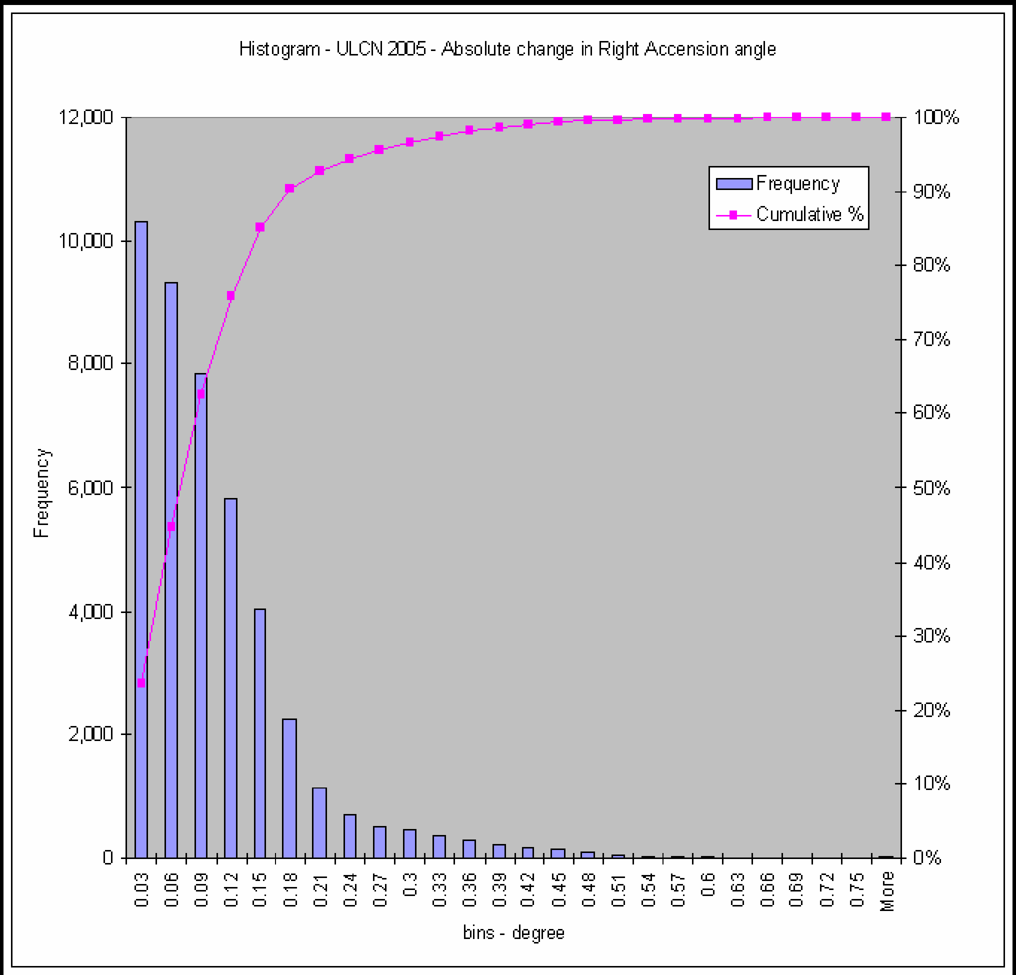
ULCN 2005 Horizontal Accuracy:
Estimate from Camera Angle Changes



No easy way to estimate accuracy – not much to compare with

- One method: Assume camera angles were perfect and average altitude of 640 km
- 0.03º supposed accuracy = 340 m
- 67% (1σ) of images moved < 0.1º = 1.1 km
- 90% < 0.2º = 2.2 km
- 99% < 0.36º = 5.1 km

(Ignores "blunders" - constraint was 1º for changes < 0.6º)

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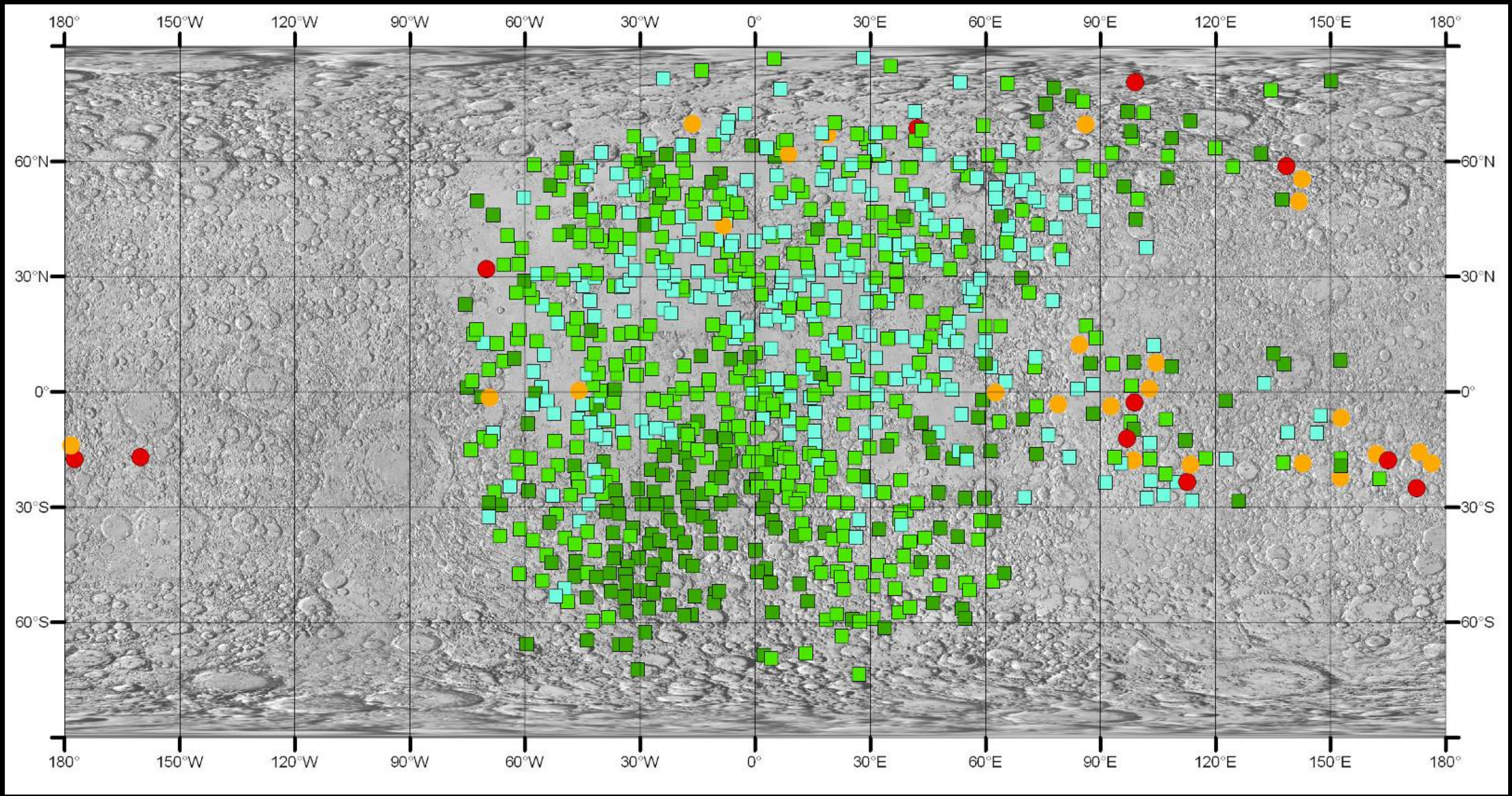
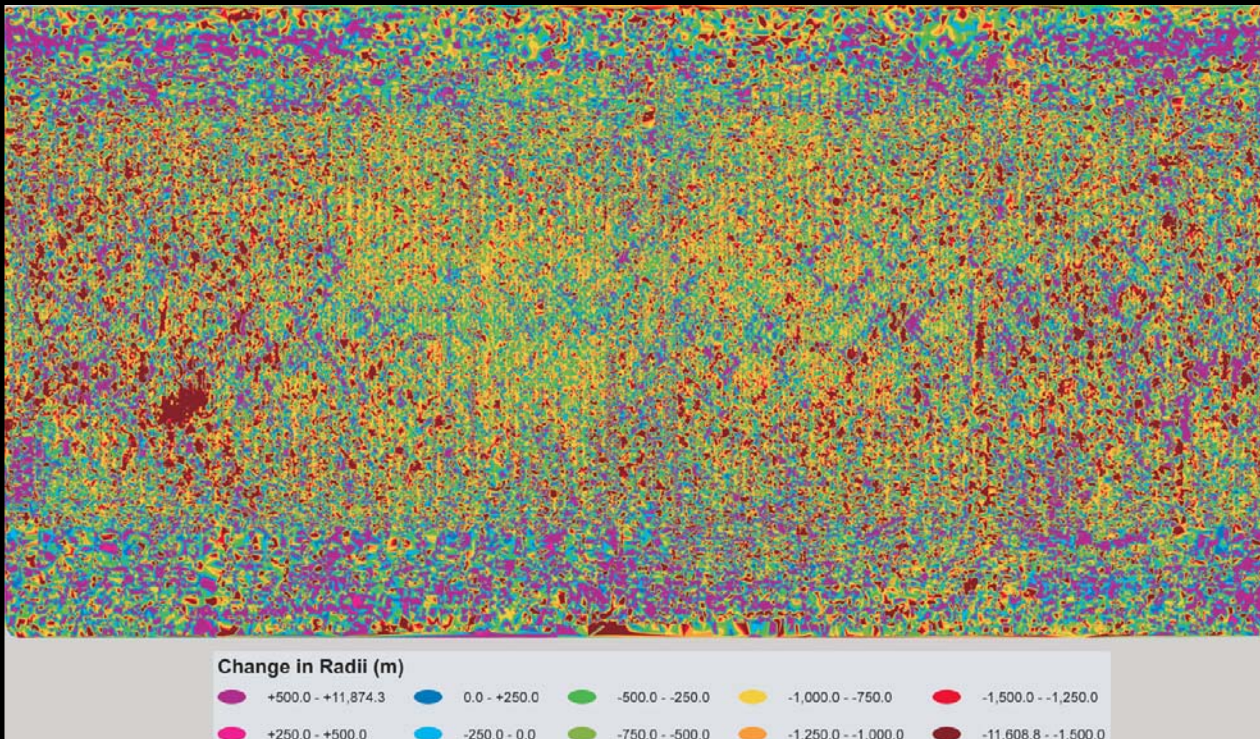
ULCN 2005 Horizontal Accuracy: Estimate from Differences to ULCN (1994)



- Second method is to compare to ULCN coordinates
- Good to < 4.5 km on near side, with mostly 0-500 m agreement with Apollo network
- Far side shows large outliers, but still several points good at 500-1500 m
- Not definite, but larger errors likely inherent in ULCN – possibly due to poor radius information – or due to our blunders in identifying ULCN points

ULCN 2005 Vertical Accuracy: Differences from Clementine LIDAR



Mean abs. differences:

ULCN points (CLCN pos.) vs. a priori: 137 ± 219 m

ULCN points after new pos. vs. a priori: 102 ± 189 m

(a priori based on Clementine LIDAR and polar stereo)

- Difference (from LIDAR and polar stereo) shows substantial signal not present in LIDAR data
- However, orbit errors and “spot” errors present at tens of m level
- ULCN also sensitive to absolute a priori changes – reliance on LIDAR and polar stereo for scale
- Differences at level of accuracy of LIDAR data (~130 m due to Clem. orbit accuracy)

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ULCN (2005) Availability

- Submitted as on-line *USGS Open File Report,* final version available soon (days)
  - Including solution files, statistics (expected vertical precision), DTMs in various formats
  - Working on way to "warp" CLCN coordinates to ULCN 2005 coordinates
  - Possible already in various software packages
- Draft available now at:

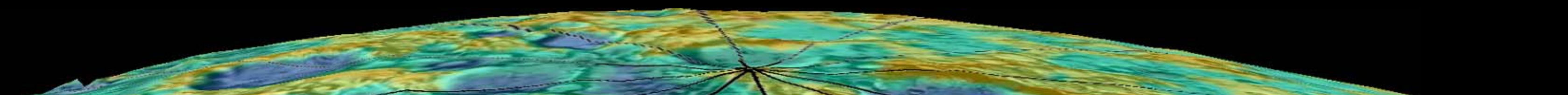
  http://extranet.astrogeology.wr.usgs.gov/Projects/DRAFT-ULCN2005-OFR/

  username: cartopanel

  password: usgspcgm
- Scientific paper also in preparation
- Funded by NASA PG&G Cartography program and USGS Astrogeology Team

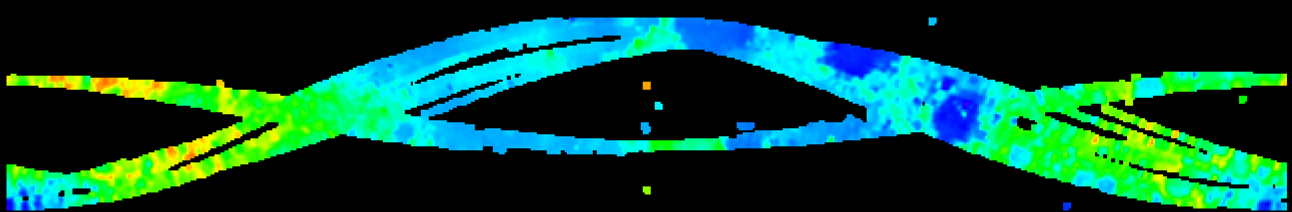
Current Horizontal Knowledge

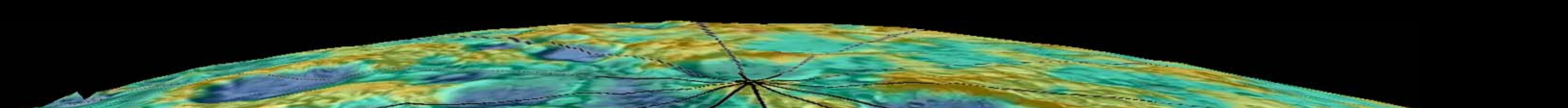
Name	Number of Points	Number of images	Horizontal Accuracy	Vertical Accuracy
ULCN	1478	n/a	100 m to 3 km	Few km?
CLCN	271,634	43,871	Few km to some>15 km	Sphere
ULCN 2005	272,931	43,866	~100 m to few km	~100’s meters



Lunar Coordinate Vertical Reference Frames

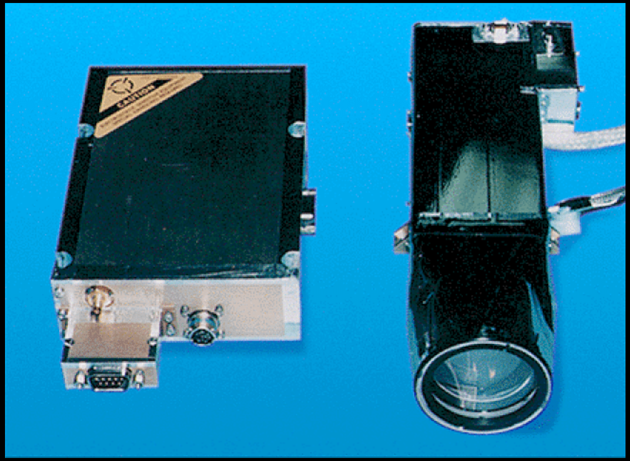
- Historical, e.g. 1970's, covered earlier
  - Earth based, LO, Apollo
- New mapping from LO and Apollo? (Later...)
- Apollo lidar:
- Clementine LIDAR
- Clementine stereo
- Earth based radar?
- ULCN 2005, just covered

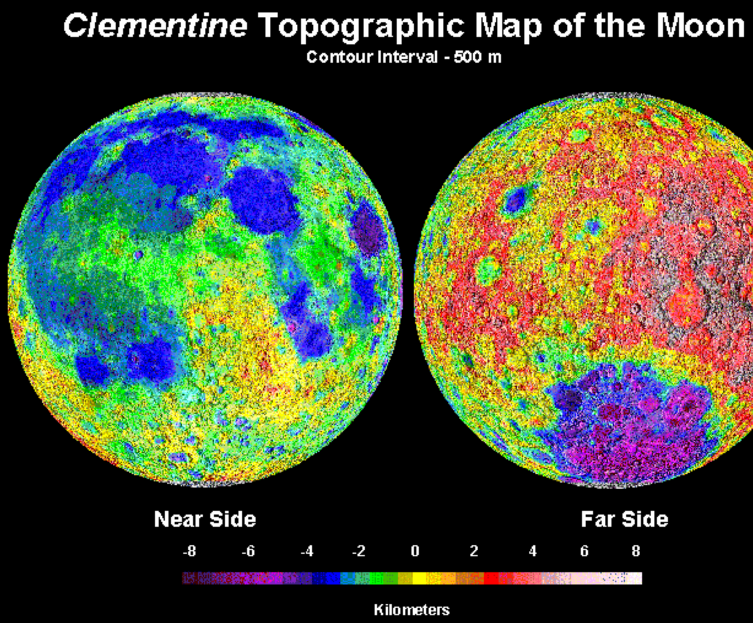




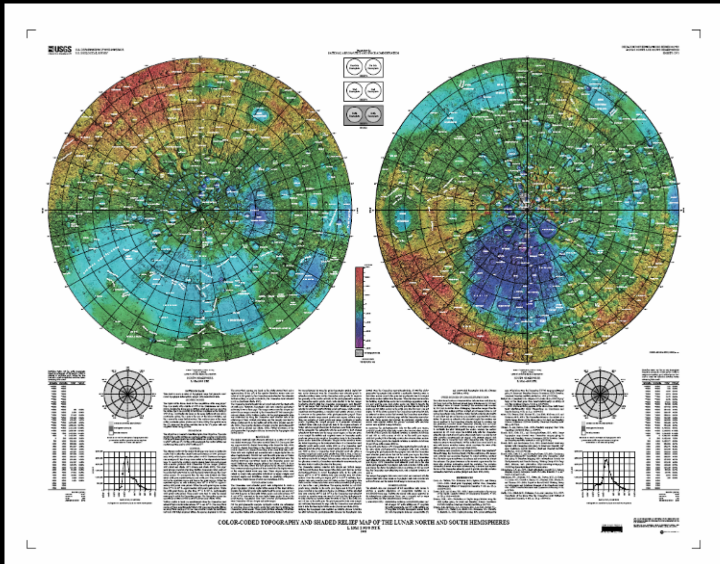
Clementine LIDAR

- 72,548 useful ranges
- Sparse coverage between ±75º
- 130 m estimated accuracy, mostly due to radial orbit error



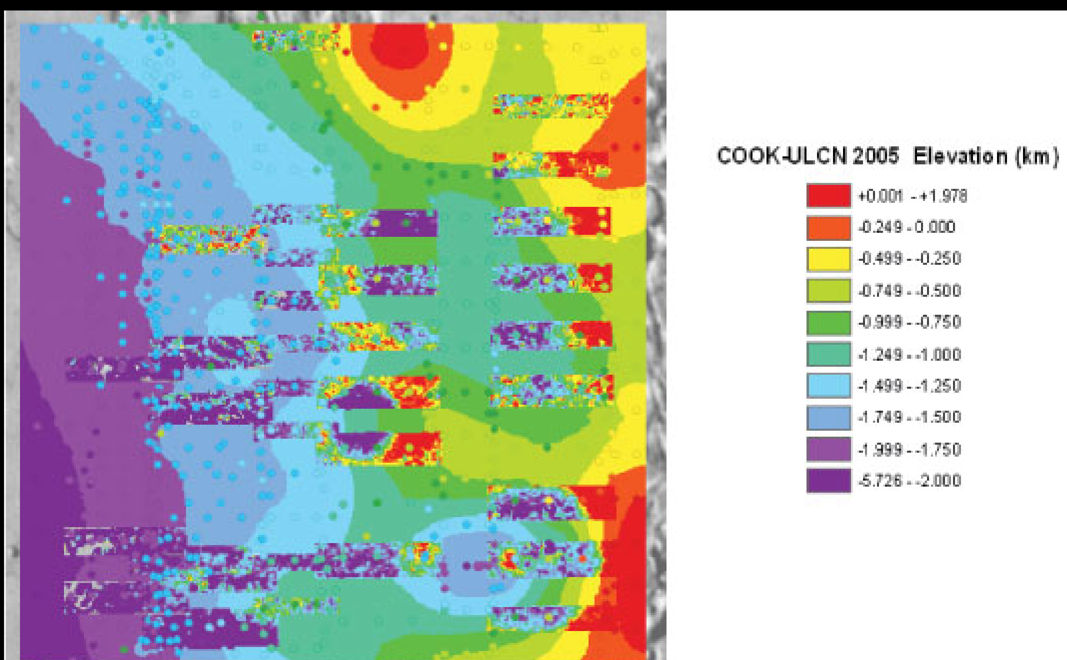


Clementine Stereo



Rosiek polar stereo

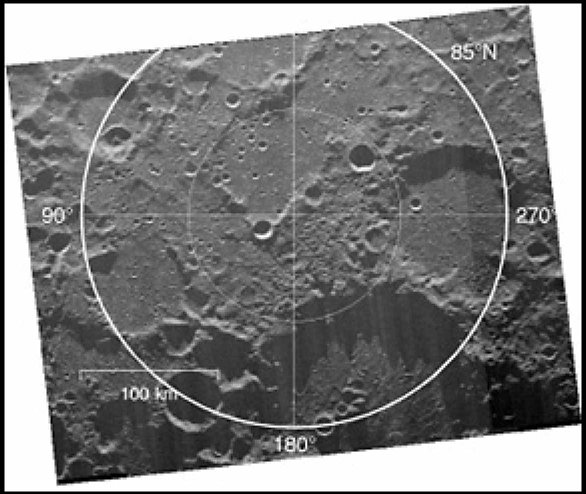
- Available as DTMs, I-maps
- Global DTM including LIDAR (a priori for ULCN 2005)
- See http://astrogeology.usgs.gov/Teams/Geomatics/photogrammetry/topography_lunar.html

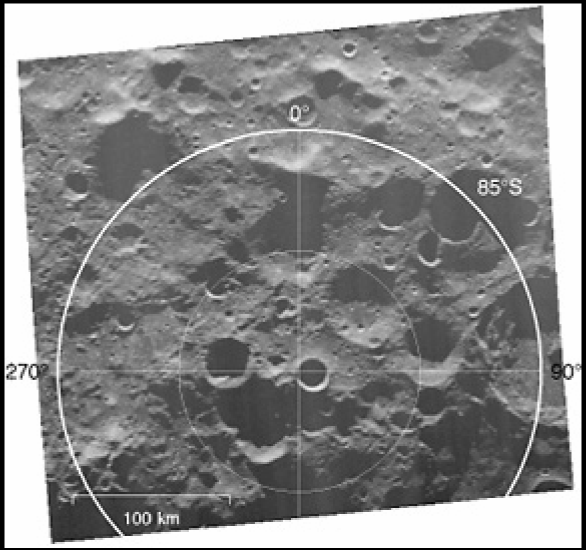


Cook et al. “planet-wide” stereo, unpublished

- See http://www.cs.nott.ac.uk/~acc/dems.html
- Shown here is difference to ULCN 2005 in Alphonsus region (center right); Alpetragius at center
- Both at 1 km GSD
- Accuracy of ~1-2 km, relative precision of 100’s of meters

Earth Based Radar





- North and south pole images here from Margot, et al. (1999)
- 150 m posts, height resolution of 50 m
- Value not clear, difficult to tie to other DTMs
  - Uncertainties unknown and precision referenced to plane of sky
  - Does not compare well to Clementine stereo
  - Data not released?

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Current Vertical Knowledge

Name	Number of Points	Vertical Accuracy	Comments
ULCN	1286	Few km?	Sparse, mostly near side
Clem. LIDAR	72,548	130 m	Sparse, between ±75°
Clem. Polar stereo	3,198,240	~1-2 km absolute	Polar only
Clem. stereo	not released	Few km absolute	Random coverage
Earth radar	~33.8x10^6 (not released?)	Few km absolute	Polar and Tycho only
Apollo LIDAR	5,629	Few km?	<20% coverage
Apollo stereo	Contour maps	As above	<20% coverage
ULCN 2005	272,931	~100's m	Global uniform coverage

III. Future Control and Products:

The Dividing Line – LRO LOLA Final Solution

Time periods:

1. Pre and during LRO mission
   - Horizontal and vertical network improvement is possible
     - Improvement in accuracy
     - Densification
   - Would support updating products or creating new ones
   - Using existing, new international mission, and LRO datasets
   - *Would support LRO, LCROSS, LPRP-2, and other upcoming mission planning*

2. Following LOLA final solution (tied to LLR frame) (~2010 June)
   - Further accuracy improvement unlikely
   - Although densification of topography still necessary
   - Existing products can be updated and new ones made in “final” frame

=> But at all times, connection of important datasets still critically important on on-going basis

- *Such efforts are not wasted*, spread effort out, provide quality control, and will allow for quick control to LOLA solution

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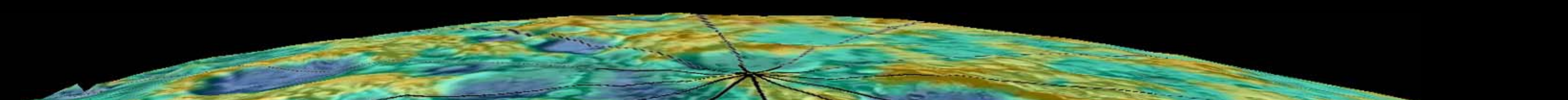
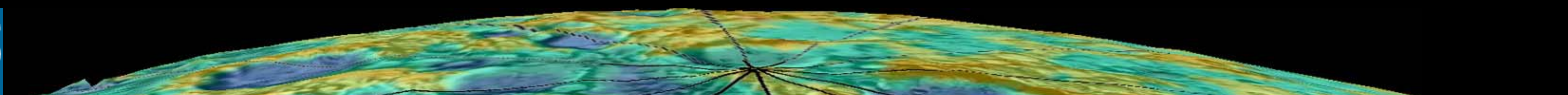
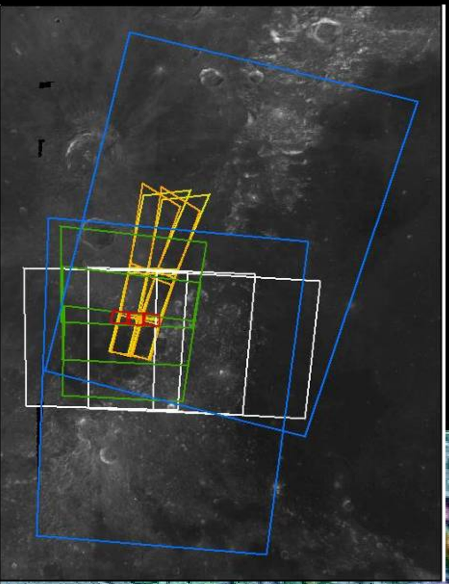


Landing Site and Regional Topographic Mapping

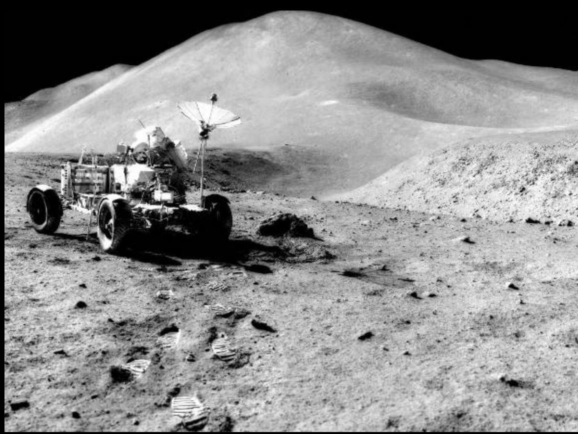
- Using LO and Apollo images
- Eventually using LROC NAC images
- *Critical for LPRP-2, later landers*
- *Critical for Constellation Program*
- Needed at least to tie LOLA solution to LLR frame
- Also could use 5, 10 m stereo from Chandrayaan-1 and SELENE

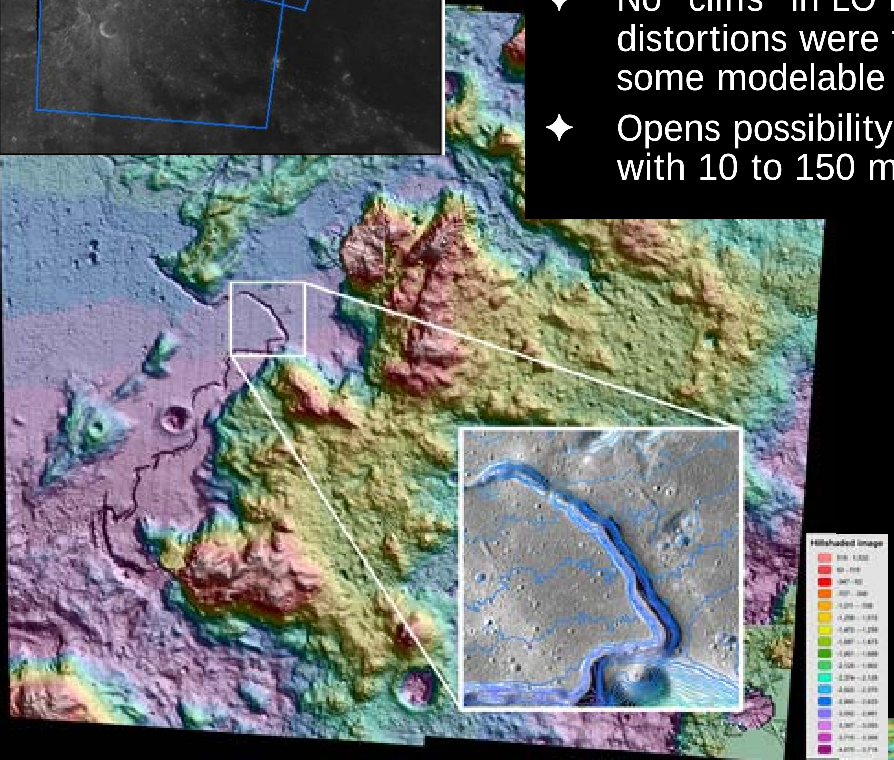


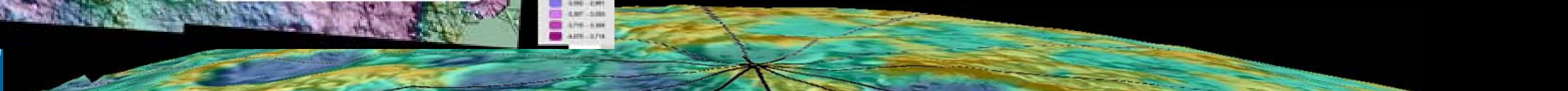
Early Product Example – Landing Site Mapping Using Digital Photogrammetry with Scanned Film Images



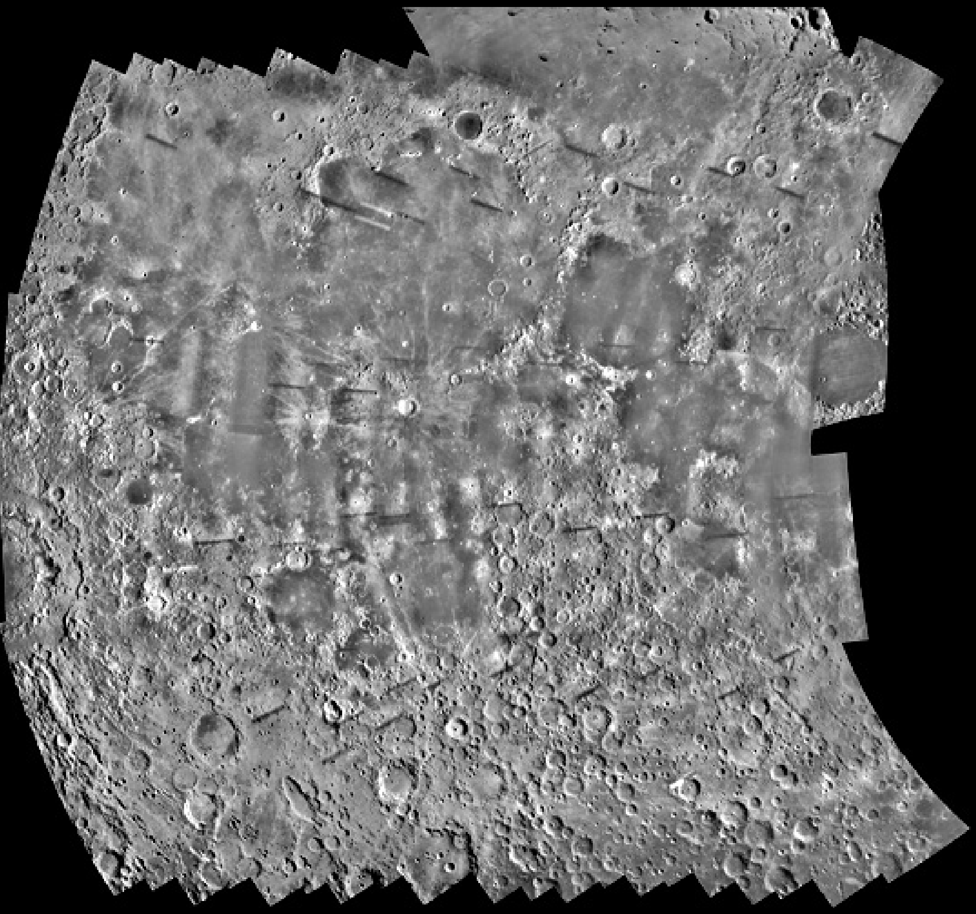
- USGS mapped Apollo 15 landing site (Rima Hadley) with scanned Apollo Metric, Apollo Pan, LO IV global HR, LO V site MR images ranging from 2 to 30 m/pixel
- Good subpixel matching except in shadows, bland areas at lowest resolution
- No “cliffs” in LO models but some other distortions were found: some random, some modelable
- Opens possibility to map 10s % of Moon with 10 to 150 m GSD



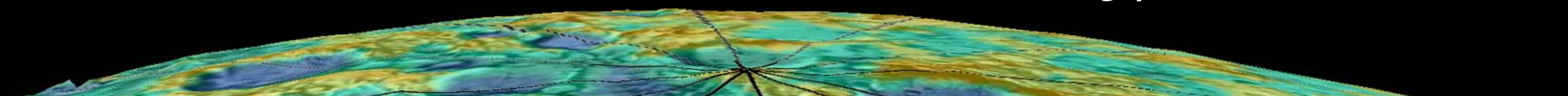




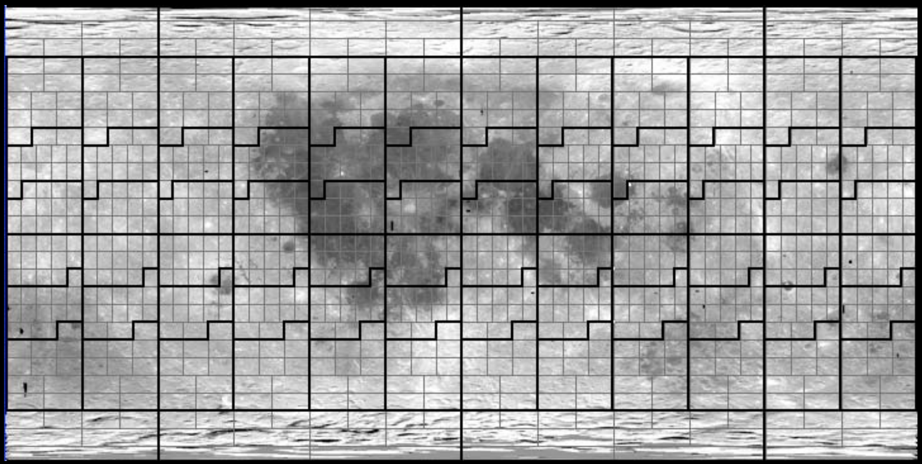
Early Product Example:
Lunar Orbiter Global Image Mosaic



- LO global coverage
  - Near side LO IV systematic (shown) at 30-40 m/pixel, some 120 m fill
  - Far side LO V 30-200 m/pixel, less systematic
- USGS is producing global mosaic at ~59 m/pixel (1/512°)
  - Highpass filtered, not photometric
  - Based on LO control net tied to ULCN 2005
  - LO CN could be merged in ULCN 2007
- Hope to complete mosaic in 2007, released online
  - Near side almost done
  - Unprojected and projected frames will also be available
- *However, funding problems*



Early Product Example:
"Re-do" of Clementine Basemap Image Mosaic

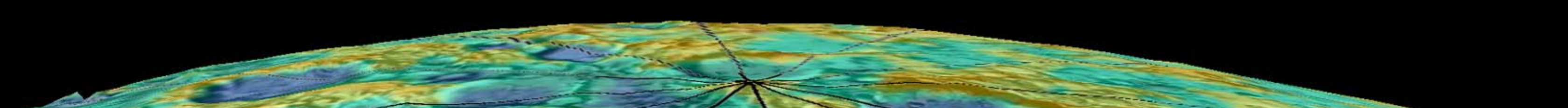


- Based on ULCN 2005, σ=~100's m rather than many km
- Will match LO mosaic precisely
- Use for LRO, LCROSS, LPRP-2 targeting
- Determine precise coordinates for features located on original basemap, UVVIS, NIR mosaics
- Match LO projection and tiling
- No photometric improvements for now to keep cost low and allow for fast production
- *Currently no funding*

Early Product Example:

Unified Lunar Control Network 2007

- Successive improvement of ULCN possible
- First step, directly add measures from:
  - Lunar Orbiter
  - Mariner 10
  - Galileo
  - Davies and Colvin, 2000
- Why?
  - Should improve horizontal accuracy
  - Check on ULCN 2005
  - More importantly ties legacy datasets together, for current and future use
  - Improves ties to LLR/ALSEP frame
  - *Should help with LRO, LCROSS, LPRP-2 targeting*
- Start funded by PG&G Cartography, *but currently unfunded due to NASA science cuts*

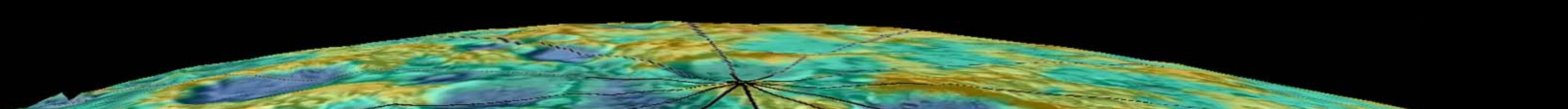


Early Product Example:
Successive improvement of global topography?

- Polar stereo re-registration
  - Move Rosiek polar stereo data to ULCN 2005 or 2007 frame
- LIDAR re-registration
  - Use ULCN 2005 or 2007 camera angles to update LIDAR positions
- Registration of Cook et al. stereo
  - Move to ULCN 2005 or 2007 frame
- Combination with Earth based radar
  - Register/combine topo data and/or ULCN to radar data
  - Improve datasets, investigate accuracy of polar radar
- Use or do combination with early lidar (foreign missions)
- *Improvement in polar areas probably critical for LCROSS mission targeting!*
- *PG&G has provided some funding for Cook et al. data processing, but that now ending due to NASA science cuts*

New Mission Early Products

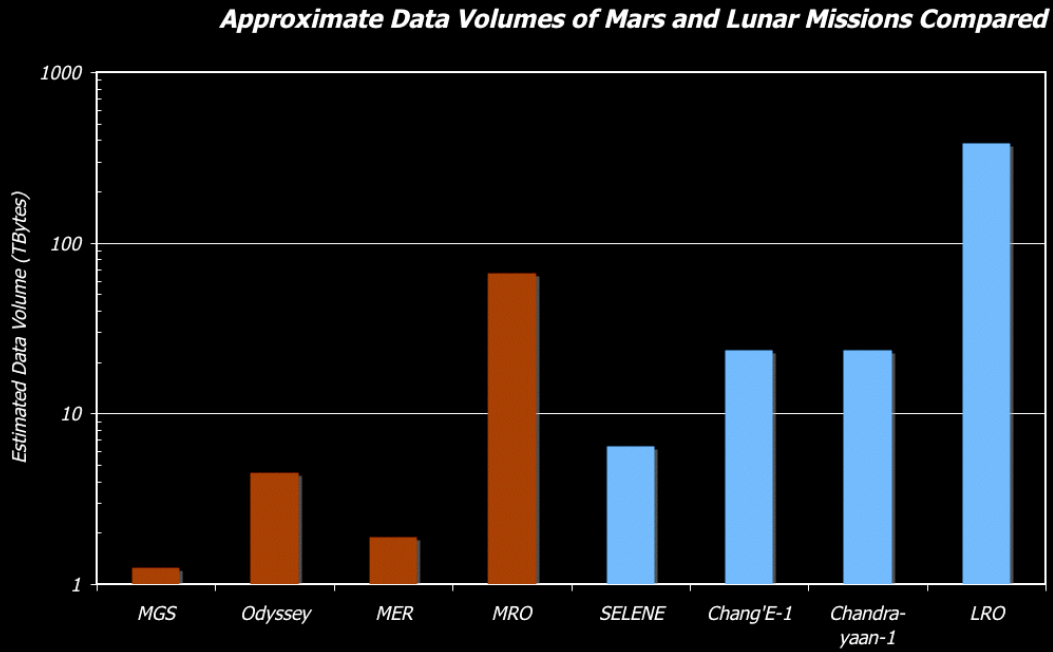
- From SMART-1 and planned foreign missions
- Early products from LRO
  - Controlled NAC (0.5-2 m) landing site mosaics
  - Controlled NAC (2 m) polar mosaics
  - Controlled WAC (100-200 m) polar movies
- Tying to ULCN useful
  - For starting mosaicking
  - Quality control
  - Improves ULCN accuracy, density
  - Ties new datasets to previous (and future) datasets
  - Again, *efforts not wasted* since measures useful indefinitely



Early Development for Massive Dataset Processing and Control

- Significant algorithm, software, and procedure development needed for coming *massive* LRO and foreign mission datasets
  - Handling large datasets
  - Control of line scanner, push frame, wide field camera images
  - Auto tie pointing techniques
  - Auto outlier rejection
  - Large solution partitioning

*The LROC NA image set is **~1600 times** the size of the entire Clementine UVVIS dataset!*



Note that the above is a log plot!

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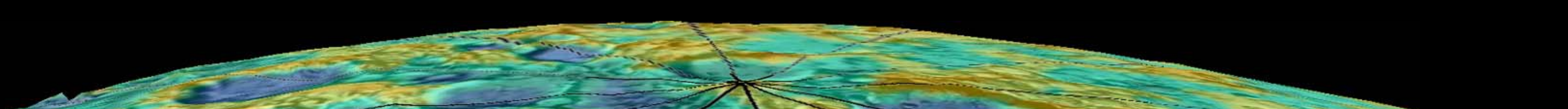
Future – Post LRO Products

- Final products from LRO, registered to LOLA (defer to Chin's presentation), but e.g.:
  - LROC NA mosaics, polar and landing site
  - LROC WA polar movies
  - LROC WA global coverage, color coverage
  - All other LRO datasets, tied to LOLA and LROC
- Numerous products from foreign missions

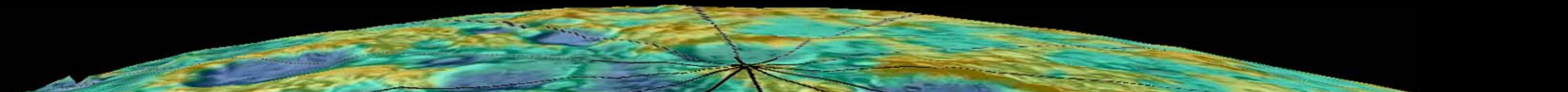
Recommendations, General (open to discussion)

- Coordinate systems/frames. Gravity field and "elevation" standards still open
- Lunar Geodesy and Cartography Working Group (LGCWG)
- Increase cooperation with international missions
- Need to develop algorithms, procedures, software now to process LRO and international mission datasets
- Continued LLR support important. New landers should have retroreflectors, and transmitters tracked by VLBI

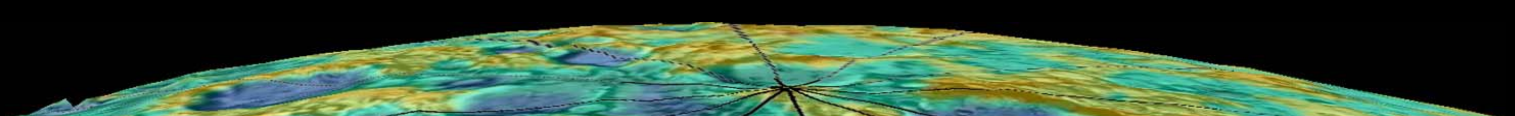


Recommendations, Products (open to discussion)

- Plan for production of landing site mapping products.
- Plan for tying together LRO datasets, particularly control of LROC images.
- Plan for tying together international mission datasets. New imaging, multi-wavelength, lidar densification, 5-10 m stereo (or 50 cm to 2 m stereo with Apollo, LO, or LROC NAC)
- Products from future missions. Integrate into frame as above. Mapping from surface.



Discussion?



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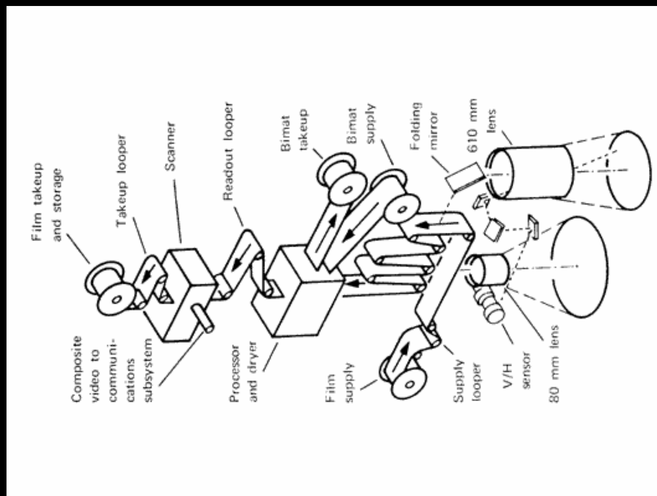
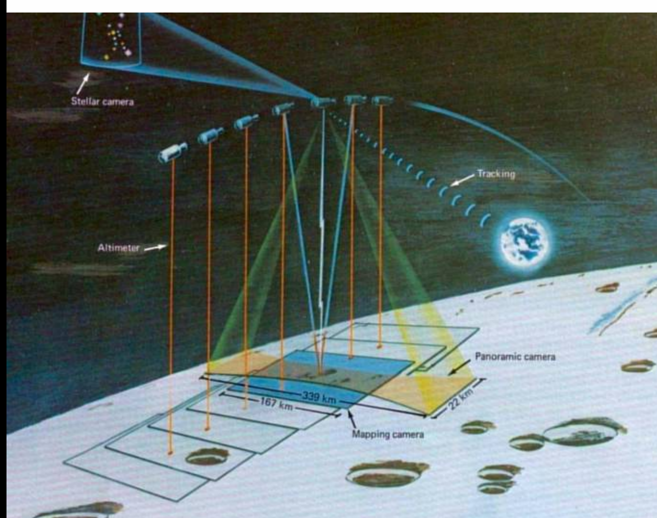
IV. Backup

- Lunar Orbiter and Apollo cameras (1 slide)
- ULCN 2005 differences to Apollo points (1 slide)
- Upcoming missions (8 slides)
- Wrap-up (3 slides)

Lunar Orbiter and Apollo Cameras

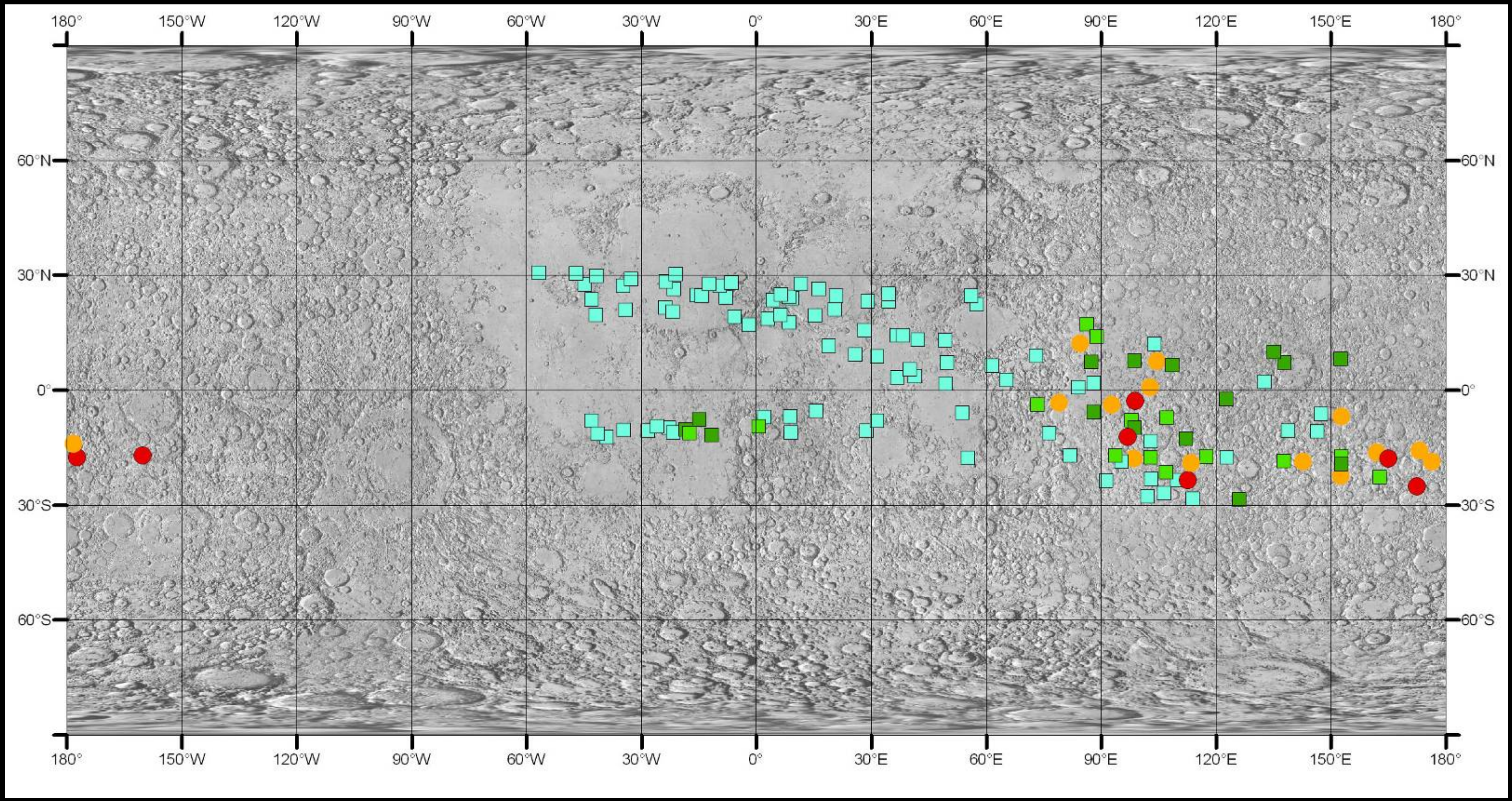




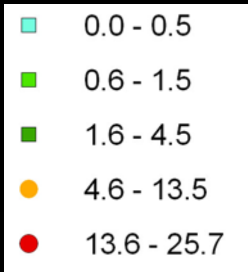
US lunar photography from orbit 1960's-1970's

- Lunar Orbiter
  - Film developed, scanned on s/c
  - Apollo site selection + global mapping from low, high orbit
  - Medium Res: 44.2°x37.9°, 4-230 m/pixel useful GSD
  - High Res: 20.4°x5.2°, 0.5-30 m/pixel
- Apollo 15-17
  - Film returned to Earth
  - Mapped zone under orbit tracks
  - Mapping Camera: 160x160 km, 15 m/pixel, stereo overlap
  - Panoramic Camera: 339x26 km, 2-4 m/pixel, stereo pointing

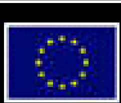
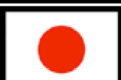
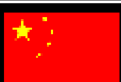
ULCN 2005 Horizontal Accuracy: Estimate from Differences to Apollo (ULCN (1994))

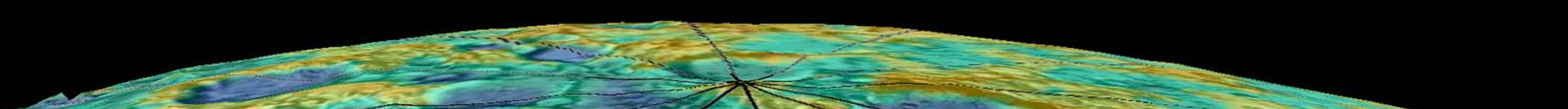


- Third comparison – compare to Apollo only (ULCN coordinates)
- Again, generally good to 0-500 m on near side
- All ranges of difference on far side, many 0-500 m, but several in 0.5 to 1.5, 1.5 to 4.5, 4.5 to 13.5, and 7 points even larger



Current and Planned Lunar Orbital Missions

Origin	Mission	Launch	Frame Camera	Scanner Camera	Image Datasets	Laser Altim	Spectro -scopy	Radar Imaging
	SMART-1	2003 Sep	>35 m pan+3 filter		Global pan single Some color and stereo		Non-imaging	
	TrailBlazer	? (2001)	High+med res video		Low sun global pan Targeted high res			
	Lunar-A	? (2004)	30 m		Terminator imaging			
	SELENE	2007		10 m 2-line	Global pan stereo	Yes	Imaging + non	
	Chang'E-1	2007 Apr		120 m 3-line	Global pan stereo	Yes	Imaging	
	Chandra-yaan 1	2008 Mar		5 m 3-line	Global pan stereo	Yes	Imaging	100 m, 10x1 km
	Lunar Recon Orbiter	2008 Oct		100 m & 50 cm	Global pan, repeated for stereo? Polar synoptic Targeted, some stereo	5-beam		100m, 15 m



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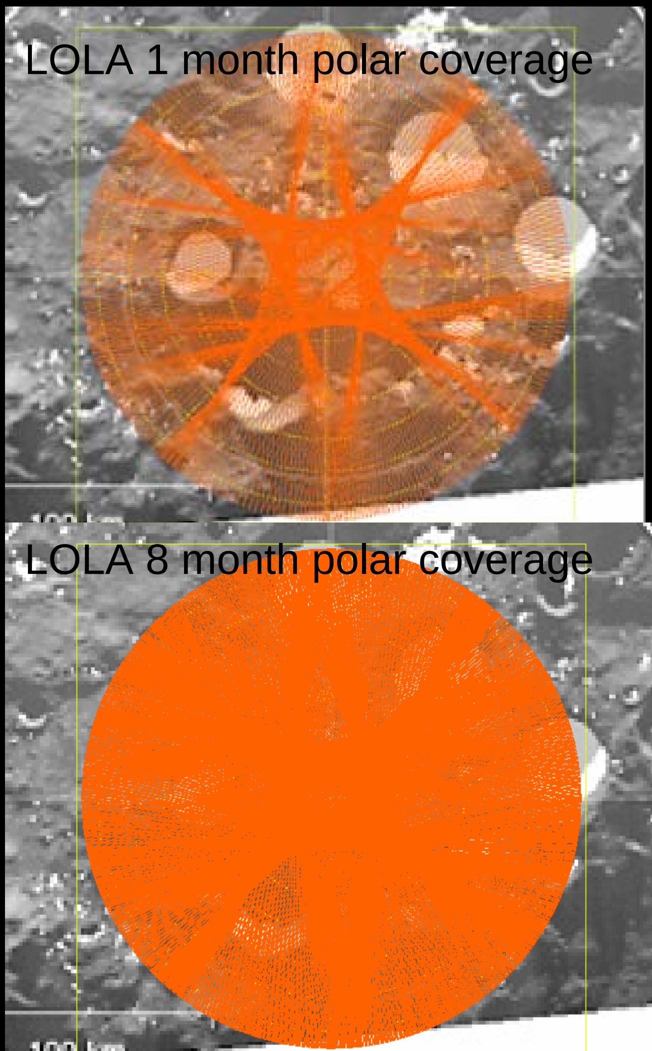
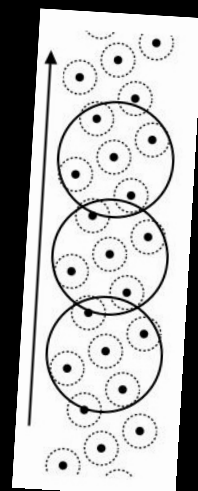
Lunar Laser Altimeters



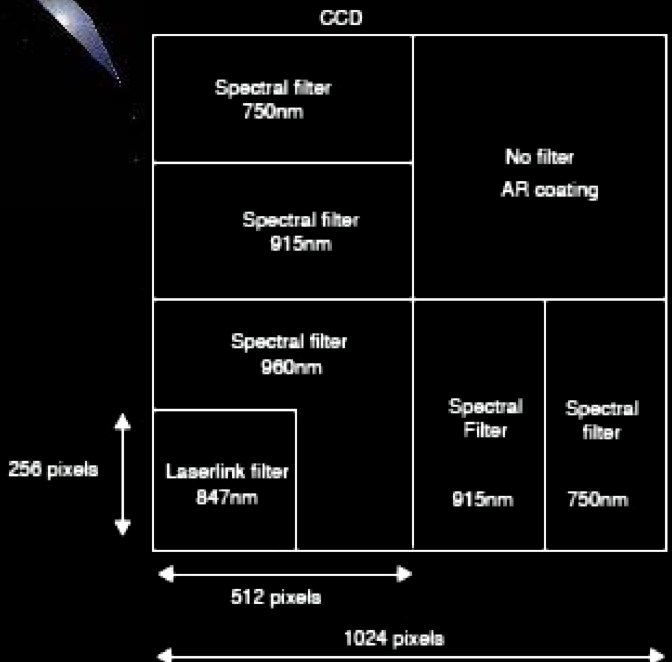


LOLA Spot Pattern

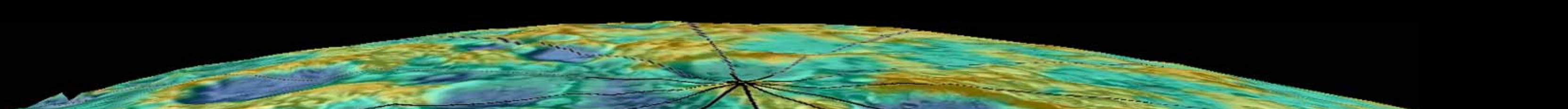
- Apollo lidar
  - Apollo 15, 16, 17
  - 1 m res., 1/20 Hz, 5628 ranges
- Clementine lidar
  - 40 m res, 130 m acc., 72548 ranges, | lat | < 60°, 1-2 km spacing
- SELENE Laser Altimeter
  - 5 m res., 1.6 km spacing, 1 Hz
- Chang'E-1
  - 5 m res., 200 m footprint, 1064 nm
- Chandrayaan-1 LLRI
  - 5 m res.
- LRO LOLA
  - 1 m res., 50 m spacing
  - 5 beams

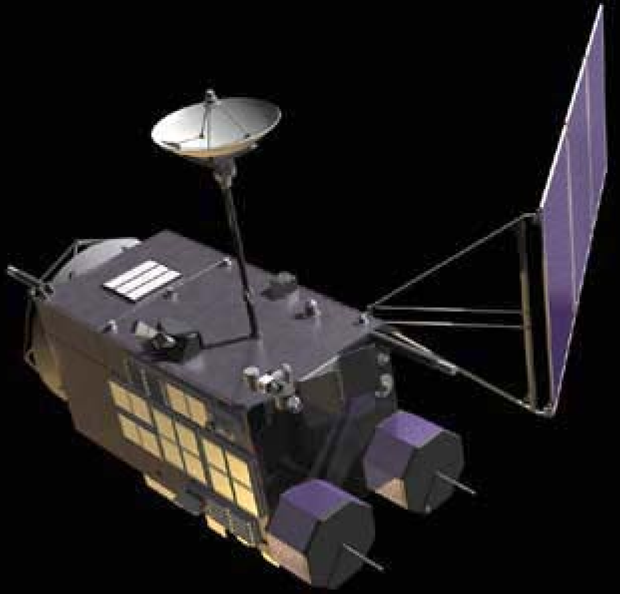
SMART-1 AMIE

Advanced Moon Micro-Imager Experiment



- 1024^2 CCD frame camera
- 5.3° field of view
- On-chip filters: clear + 3 bands + laser receiver
- ~40 m/pixel at periapse, ~150 m at equator
- Global pan coverage
- Some color
- Some stereo

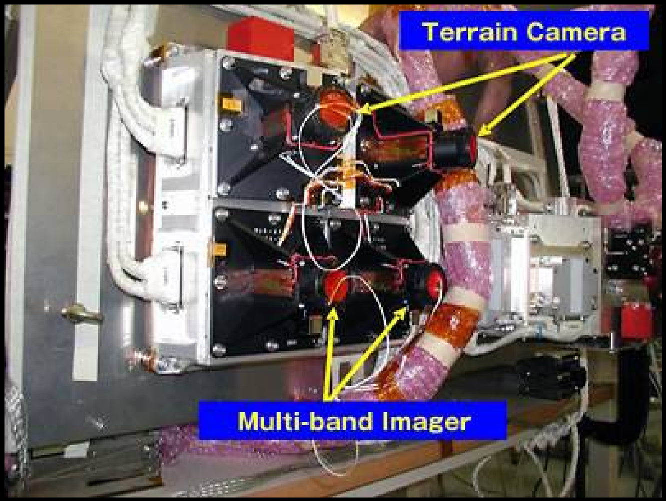




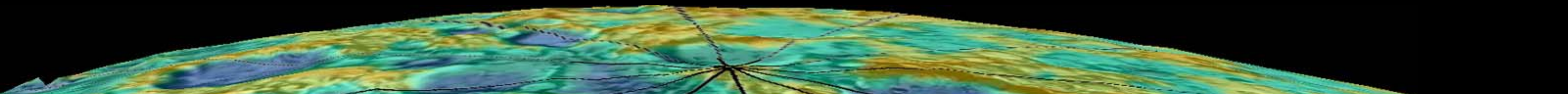
SELENE TC

Terrain Camera

- 4098 CCD pushbroom scanner camera x 2
- 22° field of view
- 2 cameras, 15° fore and aft
- 35 km swath, 10 m/pixel
- Global panchromatic stereo
- Plans include production of global DTM and orthoimages
  - Height precision 20-30 m

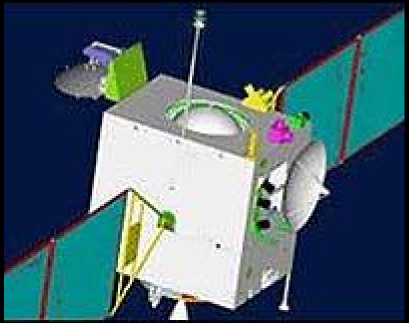


Selene – Greek goddess of the moon



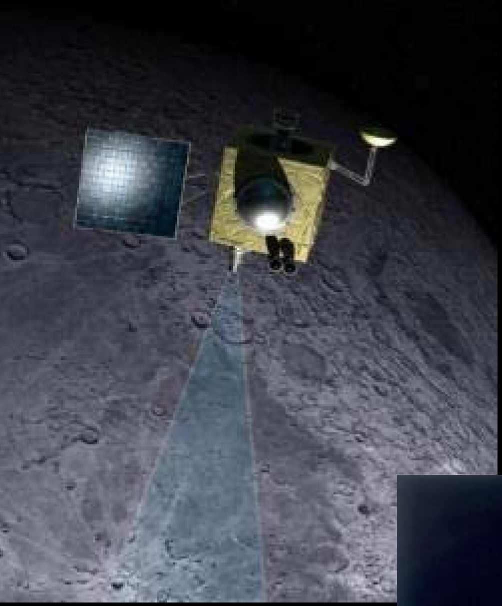
Chang’E-1 CCD
CCD Stereo Camera

Chang’e – Chinese goddess of the moon

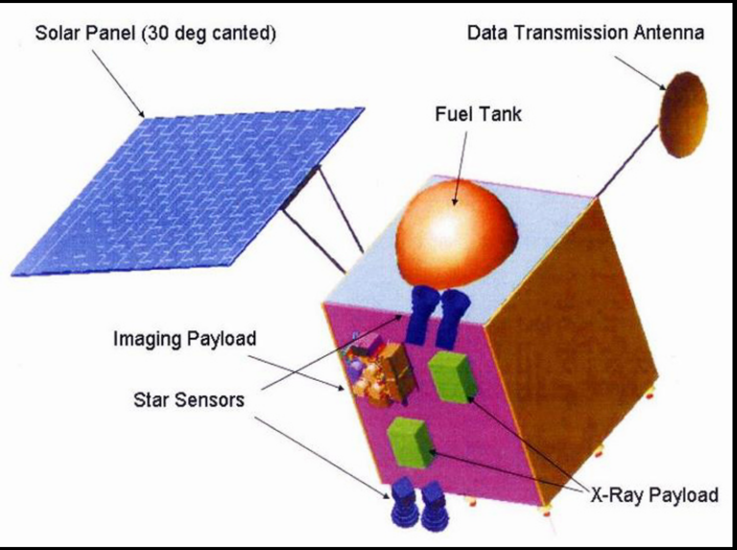


- 512 CCD pushbroom scanner camera x 3
- 3 cameras, 17° fore and aft and nadir
- 60 km swath, 120 m/pixel
- Global panchromatic 3-line stereo

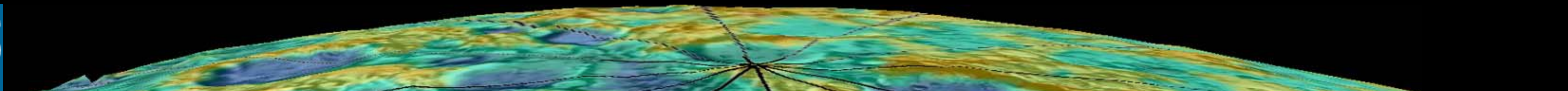
Chandrayaan-1 TMC
Terrain Mapping Camera



- 4096 CCD 3-line pushbroom scanning camera
- 20 km swath, 5 m/pixel
- Global panchromatic stereo

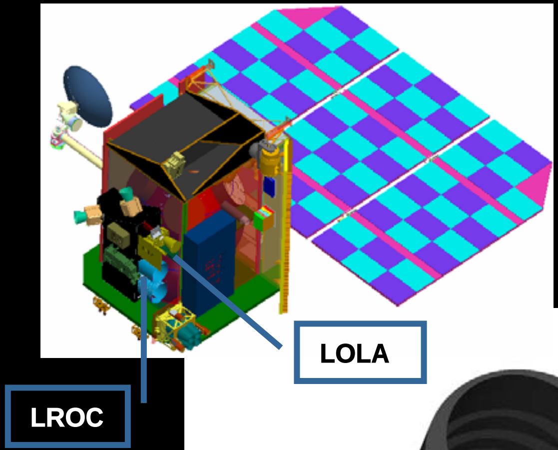


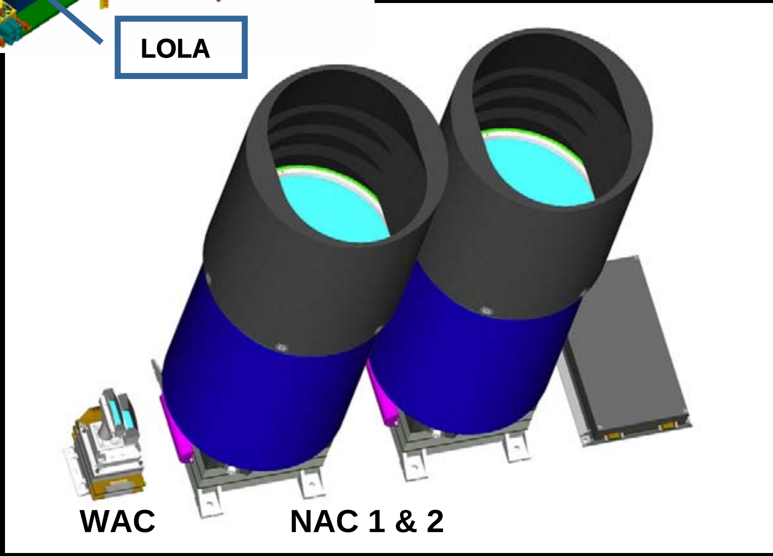
Chandra - Hindu lunar god



Lunar Recon Orbiter LROC

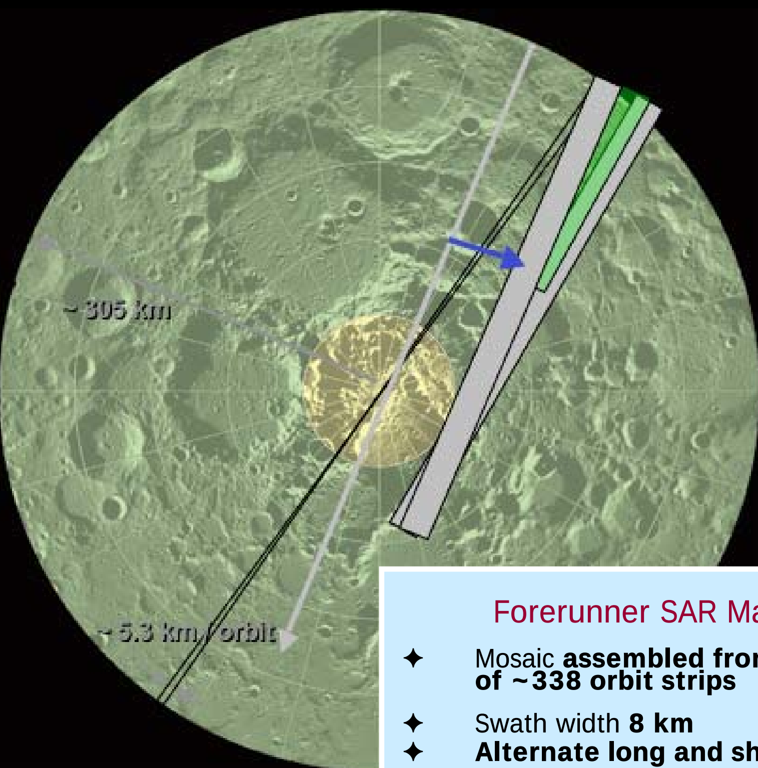
Lunar Reconnaissance Orbiter Camera





- Wide Angle Camera (WAC)
  - 1000^2 CCD frame camera
  - 90° FOV
  - On chip filters: 7 bands
  - 88-110 km field of view, 100 m/pixel
  - Global 7-color coverage
- Narrow Angle Camera (NAC)
  - 5000 CCD pushbroom scanner camera x 2
  - 2.9° FOV
  - Left and right of ground track
  - 5 km total swath, 0.5 m/pixel
  - Targeted panchromatic coverage
- Some stereo (both cameras) by off-nadir pointed repeat viewing

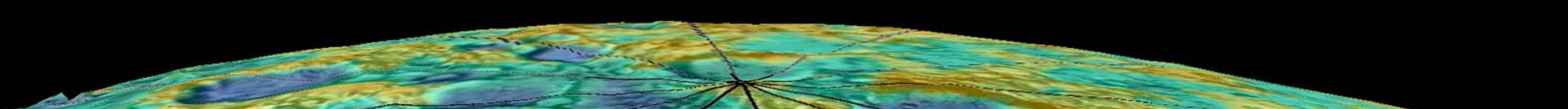
Synthetic Aperture Radars



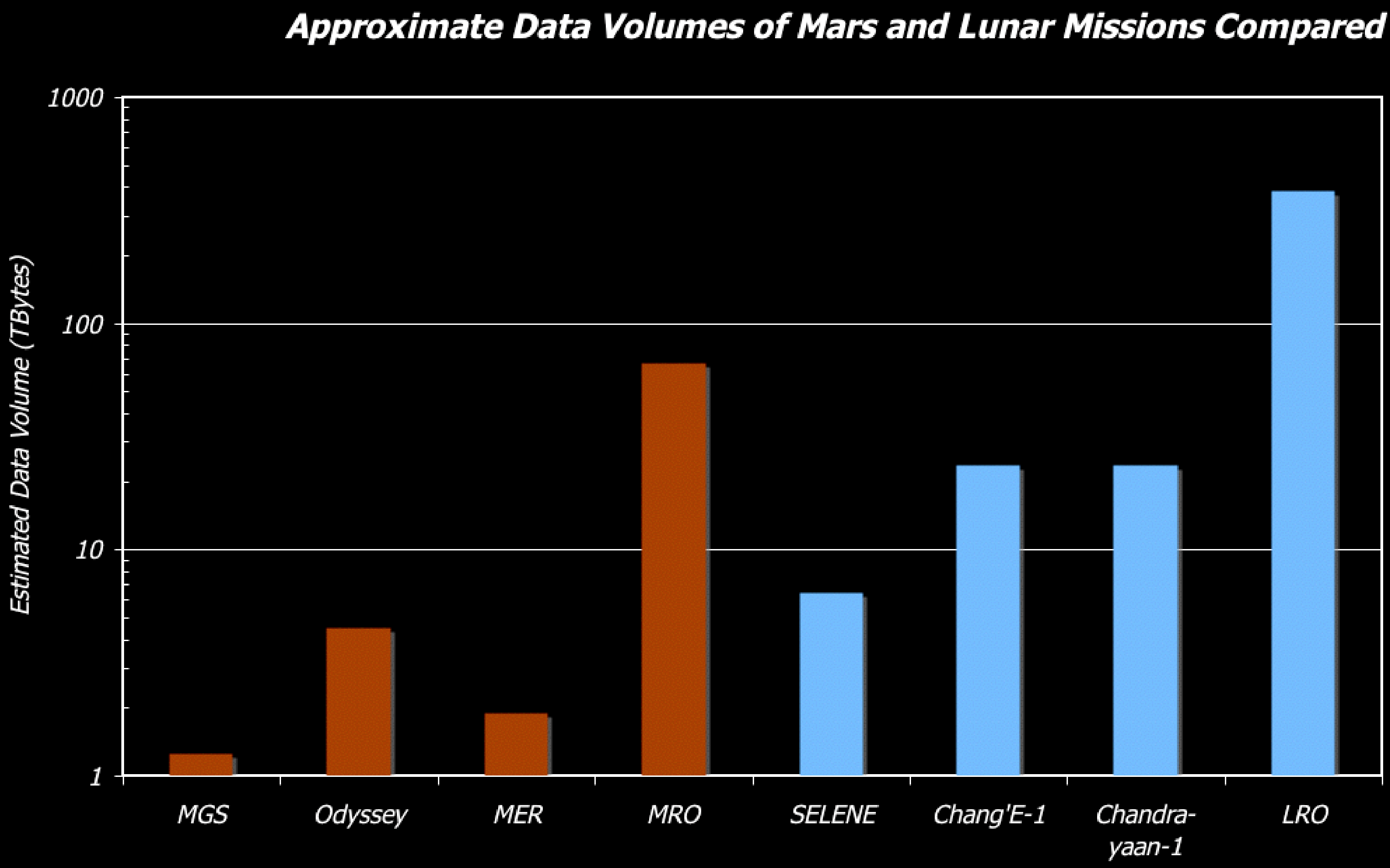
Forerunner SAR Mapping

- Mosaic **assembled from a sequence of ~338 orbit strips**
- Swath width **8 km**
- **Alternate long and short passes**
- Near-range **minimum is set by 32.85° incidence & altitude => near-polar image** gap

- Chandrayaan-1 Forerunner
  - S-band polarimetric radar
  - 8 km swath, 75 m SAR
  - Multiple coverage of each polar region from 80°-88°
  - Fill gaps at poles with 10x1 km resolution scatterometry
- Lunar Recon Orbiter MiniRF
  - S- and X-band polarimetry
  - 4-6 km swath, 75 m and 7.5 m SAR; no scatterometry
  - Interferometry to get topo
  - Engineering experiment, so very limited coverage
- Joint operations to measure bistatic scattering



Expected Data Volumes
Note: This is a log plot!



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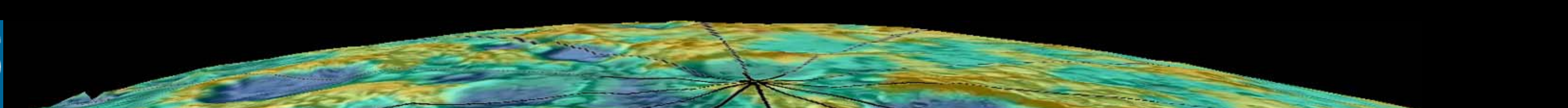
The Road Ahead

Products Needed

- Global DTMs
  - 50-100 m: lidar (4 missions)
  - 15-30 m: stereo (TC, TMC)
- Global Pan Mosaics
  - ~100 m: LO, Clem, SMART-1, Chang'E-1, LROC WAC
  - 5-10 m: SELENE, Chandrayaan
  - 0.5 m: LROC NAC (up to 10%)
- Other global/regional maps
  - Multispectral: Clem, MI, WAC
  - Hyperspectral: MI, IIM, M^3, HySI
  - Compositional: (many)
  - Microwave: (many)
- Landing site maps
  - 1.5-30 m DTMs: LROC NAC, TMC, TC, Apollo, LO
  - Orthomosaics
  - Roughness properties

Challenges

- National/international standards
- Data archiving/availability
- Automatic image tie pointing
- Lidar/image ties to a common reference system and frame
- High efficiency adjustment of pushbroom/pushframe images
- High efficiency DTM production
- Use of radargrammetry
- High data rates/volumes
- Adequate funding for cartographic products: ~1% of mission totals!



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Presentation available from:

- PowerPoint presentation: ftp://ftpext.usgs.gov/pub/wr/az/flagstaff/barchinal/LunarCrdSysLROPSWG-Archinal.ppt
- Animation called from PowerPoint: ftp://ftpext.usgs.gov/pub/wr/az/flagstaff/barchinal/apollo_Hadley_Rille_Animation_mpeg4.wmv
- Available through 2006 December at least.